AN IMPROVED METHOD FOR TESTING PERMAFROST IN SHEAR

by

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ABSTRACT

Large dimension samples of natural permafrost, obtained from the Schefferville area, Quebec, were tested in a high-capacity double direct shearing apparatus with normal pressure to 100 psi, at a test temperature of 25°F, with loading rates between 100 - 200 psi/min. Three sample sizes, 6" x 6", 4" x 4", and 2" x 2", in cross section were tested to determine shearing characteristics of the material. The results show a large increase in shearing strength with increases in confinement. Comparison tests with remolded samples show a significant reduction in shearing strength occurring with remolding.

ACKNOWLEDGEMENTS

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The Iron Ore Company of Canada, Schefferville, assisted the author with his sampling program, and provided facilities for some of the testing. Mr. O. Garg was especially helpful.

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I - INTRODUCTION

1-1 Statement of Problem:

The mining industry constitutes a very important contribution to Canadian life, both economically and politically. It has been estimated that Canada's total mineral-dependent labor force could comprise about 12 per cent of the total labor force. Including the service industries related to mining, the mining industry accounts for approximately 20 per cent of Canada's Gross National Product.(1)* The quest for minerals has been responsible for considerable northern development, necessitated by the declining ore reserves in the southern regions.

The development of resources in the Arctic and Sub-Arctic presents unique challenges. In Canada, approximately one half of the total land area is underlain by permafrost (fig.1) Thicknesses of up to 530 m. have been recorded on Melville Island, and it is projected that depths to 1000 m. could be anticipated.(2) As defined by Muller (3) "permafrost" was the thermal condition of soils and rocks at temperatures that remained below 0°C continuously for two years or more. The functional definition that is now accepted includes all frozen ground, even that which is frozen for only one year(4). A typical section is given in fig. 2, showing the active zone,

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* Parenthesized numbers refer to references in the Bibliography.

which is subject to intermittent freezing and thawing; the unfrozen ground called talik; and the areas containing permafrost.

Many large projects, notably the New Quebec-Labrador iron ores, the Alberta Tar Sands, the High Arctic oil and gas fields, and the nickel and asbestos deposits in the Deception Bay area of Ungava, Quebec, are in such areas. The presence of continuous or discontinuous permafrost offers challenges to transportation and materials handling systems, mining equipment technology, and the design of mine excavations.

The designing of structures on or in permafrost zones, and of open pit or underground excavation in these areas, necessitates an understanding of the behavior of frozen soil and rock. If the method of construction is such that the permafrost is not allowed to thaw, then the strength of the natural material can be used in calculating bearing capacities, or the stabilities of slopes and retaining structures. These calculations require knowing the shear strength properties of permafrost in its natural state.

The purpose of this project was to determine how these shear strength parameters could best be obtained quantitatively for a natural permafrost material.

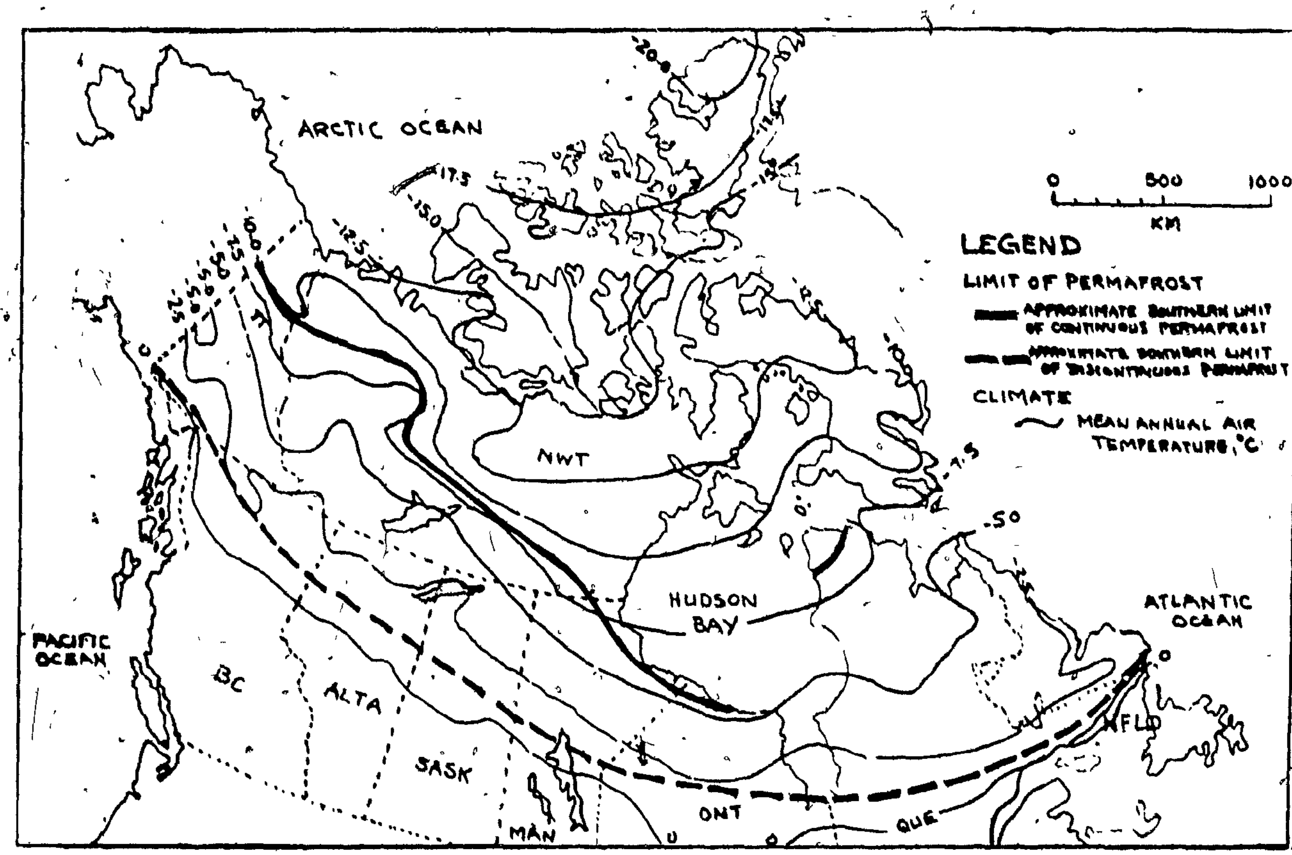


FIGURE 1 - PERMAFROST IN CANADA
(after BROWN and PEWE (4))

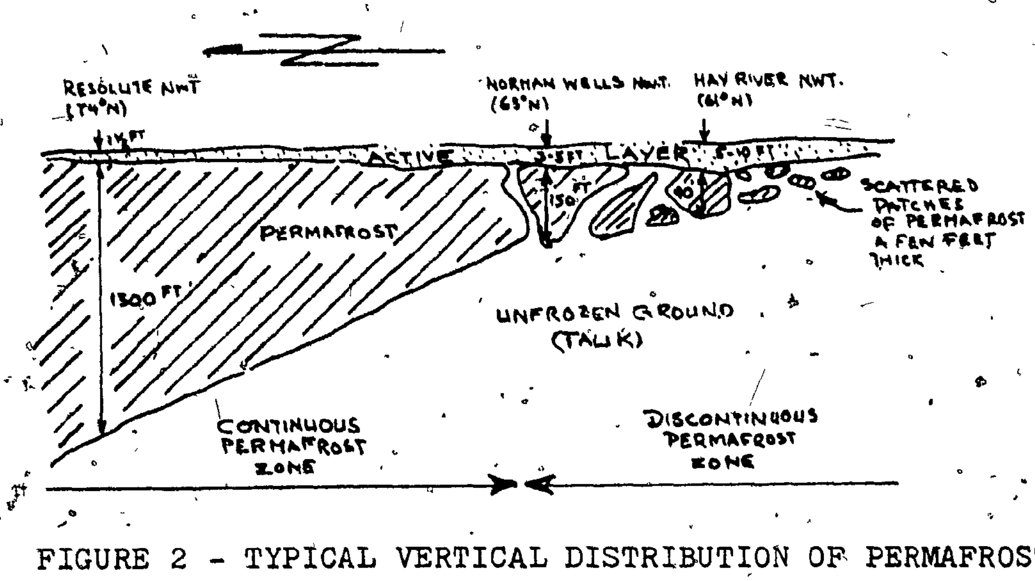


FIGURE 2 - TYPICAL VERTICAL DISTRIBUTION OF PERMAFROST
(after BROWN and PEWE (4))

1-2 Outline of Project:

The strength of most geological materials is heavily dependent on their fabric, that is, the system of fractures, structures, and the physical arrangement of the discontinuities. Furthermore, bedding planes, ice lenses, and natural gradation of granular materials will lead to highly variable anisotropic properties.

In the past, testing has usually involved small samples (5,6). The sampling procedures have resulted in the selection of samples which did not contain structure and which were relatively homogeneous. Such samples would not necessarily reflect the true character of the in-situ material. It is believed that larger samples, which do accomodate more structure and which reflect more of the fabric of the natural material, would yield more meaningful results. Furthermore, in the preparation of samples from natural permafrost, the usual methods of cutting and trimming cause considerable surface disturbance, which, in all probability, affects the strength of the material. It is believed that larger samples would tend to reduce the area that is subjected to this disturbance.

The purpose of this study, then, was to design a shear testing machine in which large samples of natural permafrost could be tested.

A double direct shearing apparatus, with a vertical shearing capacity of 100 tons and a horizontal axial load capacity of 25 tons was designed by the author and built under his supervision in the machine shop at the Institute for Mineral Industry Research of McGill University, Mont St. Hilaire. The testing machine can accomodate 6" x 6", 4" x 4", and 2" x 2" samples. The separation between the shear box halves is adjustable to a maximum 3/4". The loads are applied manually through a hydraulic system. The apparatus has been calibrated and has been found to perform effectively.

Natural samples of permafrost were obtained by the author during a trip to Timmins Mine at Schefferville, Quebec. These were relatively uniform in appearance, and were taken from approximately the same mining horizon and in the same geological unit, namely the Middle Iron Formation, which is mainly composed of hematite. The frozen material had few visible ice lenses. When thawed, the material is best described as a granular soil, sandy silt to the touch.

At the time of selection, the samples were packed in ice chests, stored in a freezer overnight, and then air shipped to Montreal. After being transported to the Institute for Mineral Industry Research, they were stored in a temperature controlled refrigeration unit. Two large shipments of samples were made.

Although it cannot be claimed that the material was "undisturbed" with regard to temperature, since the actual ground temperature was not known, and since various temperature changes could have occurred during transportation, it should be noted that the samples arrived in a solid state and were maintained in that state. If some thawing had occurred, it was at the surfaces of the rough samples only.

At least 3/4" of the surface was discarded in the cutting and trimming processes. It can be assumed that, for all practical purposes, the structures in most of the samples were undisturbed, except due to relaxation effects of removal of overburden pressures.

While in Schefferville through the courtesy of the Iron Ore Company of Canada, the author used the company's facilities to conduct shear tests on material which had been permitted to thaw. This material had been obtained from the same location as the frozen samples shipped for testing. Five tests were conducted, using a Wykeham Ferrance 10 ton capacity shearing apparatus. In addition to the shearing parameters, the moisture contents and a grain size distribution analysis were obtained.

At Mont St. Hilaire, the samples of permafrost were cut to size in the cold room. Several preparation techniques were tried before the author established that using a band saw for rough cutting and a portable grinder for final trimming produced the most acceptable samples.

These were then tested in shear, either with or without normal pressure. The ambient temperature during storage, preparation and testing was maintained at 25°F. This temperature was selected to replicate a typical field temperature and to permit comparison with other results published on the subject of shear testing of frozen soils. During testing, the axial load applied was held constant throughout the test. Observations of movements versus the loads applied were made in addition to the maximum breaking strength. The loading rates were calculated from the shearing strength and the total time to failure. Moisture contents, densities, and some grain size analyses were performed in addition to the shear tests.

Remolded samples were prepared from the remnants of the natural materials tested. After thawing, the material was packed into molds and refrozen. The remolded samples were then tested under the same conditions as were used for the original samples.

Three sample sizes, 2" x 2", 4" x 4", and 6" x 6", were tested, and the results were compared to determine if the effect of sample size to shearing strength could be quantified.

The results obtained from the experimental work suggest many considerations that must be taken into account in the testing of natural permafrost materials. These will be discussed in the sections concerned with the analysis of the results and with the writer's conclusions and recommendations.

II - THEORY and REVIEW of RELATED LITERATURE

2.1 General Concepts:

The current methods employed in the design of open pit slopes, retaining walls, or foundations are dependant on the knowledge of so-called "shear strength" parameters. These would be the properties of cohesion and angle of friction which will be defined below. They reflect the resistance offered to movement along a particular plane. As the most common type of failure seems to be shear failure, their importance can be seen.

The resistance to shearing can be expressed as a linear relationship denoted by the familiar form of the Coulomb-Navier criterion. That is, failure occurs when:

$$\tau_m \geq c + \sigma \tan \phi \qquad (1)$$

where: τ_m = maximum shear stress

c = cohesion

σ = normal stress

ϕ = angle of internal friction

Thus, accepting the relationship between maximum shear stress (stress in the direction of movement) and the normal stress (stress normal to the direction of movement), we see that the parameters c and ϕ are constants for any particular material. Determining these constants, either by laboratory or in situ methods, leads to establishing the resisting forces to movement. The stability of the earth structure is thus determined by comparing the forces tending to produce a failure to the forces tending to prevent it (7).

The simplistic view offered in equation (1) is, of course, an idealization which should be used only as a working model. The factors affecting the various parameters must be appreciated as well as the inherent limitations to the theory when applying it to the practical design problem.

A discussion of the shearing strength of permafrost necessitates a full appreciation of the mechanics of frozen soils in general, and of natural permafrost in particular. Much of the work done in the study of permafrost has been concerned with either the delineation of permafrost, or, especially, with trying to establish its physio-chemical properties. Until a better understanding of these properties can be reached, investigating the mechanical properties of permafrost will be difficult. This explains the unfortunate lack of information available to the practicing design engineer.

Science and engineering seem to approach problems with differing points of view. The engineering viewpoint is usually purely utilitarion, that is, to formulate solutions to problems in a practical if not rigorous way. The scientific approach is a careful exercise in determining the true nature of the material studied, consistent with all the laws of nature. Although engineering as a whole is usually thought of as appied science, the geotechnical branch particularly is establishing a more empirical philosophy, generating working hypotheses not always in conformity with the rigorous scientific theories being developed.

The present study tries to relate the various scientific information available, while keeping the emphasis on the "engineering" approach as outlined above.

2.2 Review of Related Work:

Much of the pioneering work in the study of the properties permafrost and frozen ground has been done by Soviet authors. The most notable publications are works written or edited by N.A. Tsytovich, M.I. Sumgin, and S.S. Vyalov. Most of the major works are available in translation (8,9,10).

S.W. Muller's "Permafrost or Permanently Frozen Ground and Related Engineering Problems" (3) was probably the first notable North American publication. Much of the information included was compiled from the writing of Soviet authors. Although much of the information is useful, descriptions of testing procedures are lacking. Thus, it is hard to ascertain the proper significance of the results presented. It is noteworthy to mention that Muller is credited with originating the word "permafrost".

Among the various organizations in North America, the United States Army Corps of Engineers and the National Research Council of Canada are the most active in conducting or sponsoring research. These organizations also provide translations of works by foreign authors.

In connection with this project, the McGill Sub-Arctic Research Laboratory at Schefferville, Quebec produced much needed field information (11,12,13). The reports contain discussions of the climate, terrain, and geology of the area.

Previous work on determining engineering properties of frozen materials from the Schefferville area was done by S.M. Yap (14). Five types of frozen geological materials were tested to determine resistivity, thermal conductivity, compressive strength, shearing strength, and sonic velocity at temperatures between 28°F and 36°F. The shear strengths determined were at zero confinement, using one cubic inch samples.

R.N. Yong's work (15) includes a review and discussions of the important variables affecting the shearing strength of frozen soils. A double ring shearing device was used in the experimentation. Effects of temperature, lateral confinement, void ratio, and water content were examined, using cohesive and cohesionless reconstituted soil samples.

Quite recently, (July 1973) the second international conference on permafrost was held at Yakutsk, U.S.S.R. The proceedings of the North American contributions to the conference can be used as an up-to-date guide to the available information and thinking on frozen ground and permafrost. In a review of available information on the mechanical properties of frozen and thawing ground, Anderson and Morgenstern note that "...the study of frozen soils is clearly in the stage where most work is being done on reconstituted frozen soils..."(16). This situation handicaps the researcher gathering information on the properties of natural permafrost.

In summary, although the available literature does help in setting up an acceptable framework for the present study, it should be realized that, in fact, very little research into the study of the shearing strength of natural permafrost has been done or is available.

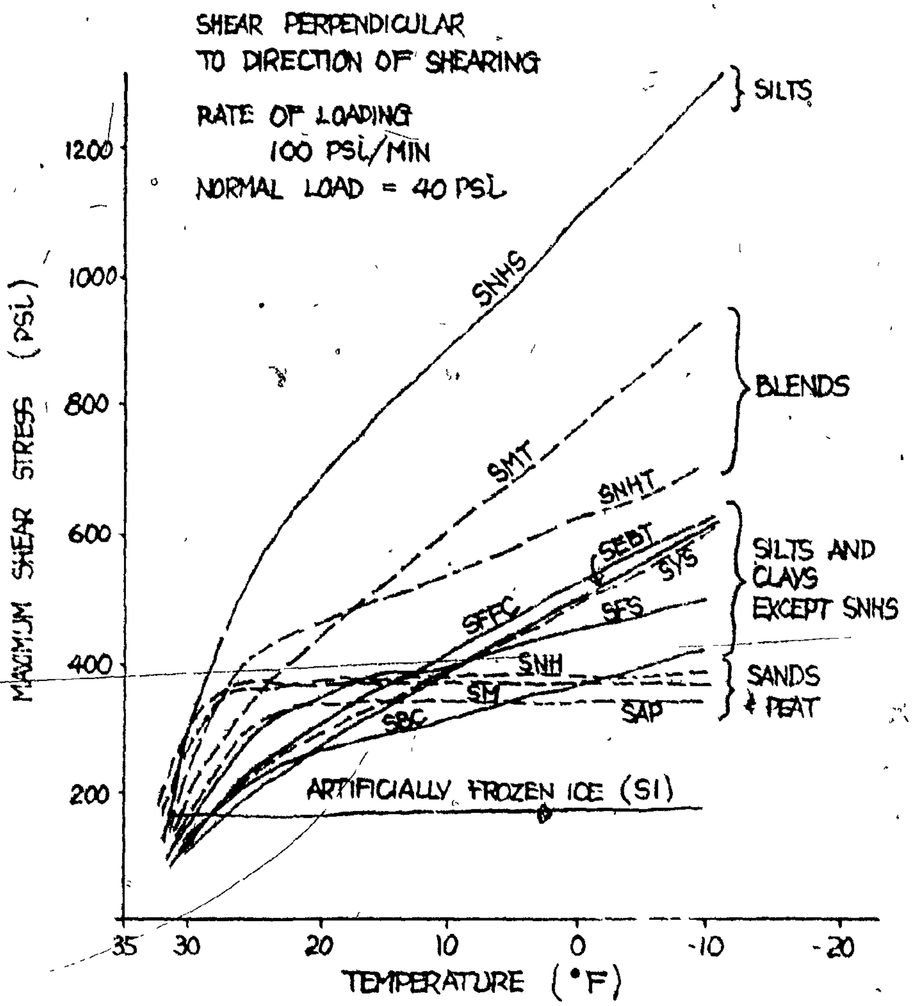
2.3 Factors Influencing Shearing Strength of Permafrost:

Although the fundamental processes and variables that control the mechanical behavior of frozen ground are not fully understood, engineering requirements necessitate at least some theoretical models and methods in order to give practicing engineers some confidence in the design of earth structures made of these materials. The processes and variables which have been isolated are varyingly interdependant. In some cases, this interdependance is difficult to quantify. A further difficulty arises in translating laboratory studies to field conditions, and again in comparing soil types of differing structure.

F.H. Sayles discusses shearing strength in terms of the two accepted parameters of cohesion and angle of internal friction. Following a Russian work by Vyalov and Tsytovich (17), he describes cohesion as "attributed to molecular forces of attraction between particles, physical or chemical cementing of particles together, and cementing of particles by ice formation in the soil voids". These are all dependant on temperature. However, the internal friction depends on " ice content, the soil grain arrangement, sizes, distribution, and shape; and the number of grain-to-grain contacts". Although ice content is temperature dependent, all the other variables are not.

Temperature is therefore a significant factor in the strength characteristics of a material. It has been found that, as temperatures are lowered, the strength of the frozen material increases (figures 3-4). This increase in strength is thought to be due either to an increase in the strength of the ice phase or to an increase in the quantitative amount of ice in the material. At temperatures found in field conditions (to -15°C) (19), the latter explanation appears more important. Also of significance is the temperature history of the permafrost, as this affects both the ice content and the ice structure (16).

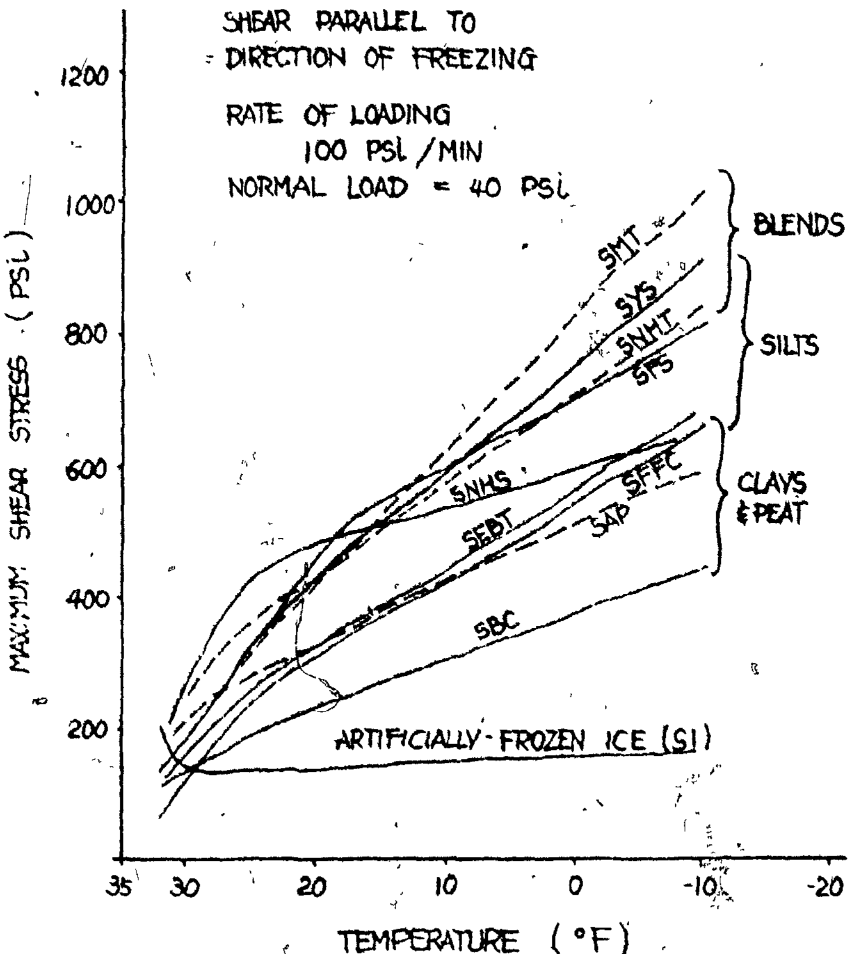
The existance of unfrozen water at below 0°C is well known; however, its quantitative effects on strength and its determination in natural samples is not well documented. P.J. Williams (18) has observed that in a sample of previously unfrozen iron ore material, the unfrozen water content on first freezing can be as high as 3% at -5°C. The effect of unfrozen water is thought to be more significant in clays and silts, which contain, due to their structures, bound or "double layer" water, requiring much lower temperatures than free water to freeze. It can be assumed that the effects of unfrozen water will not be as pronounced in granular materials, due to the absence of ionically bound water. The increase in strength of the frozen material can then be related to an increase in the total moisture content, reflecting the increase in the ice content (figure 5). Thus, a simple model containing a combination of two constituents, soil



LEGEND

SM	- McNAMARA CONCRETE SAND	SFS	- FAIRBANKS SILT
SNH	- MANCHESTER FINE SAND	SYS	- YUKON SILT
SMT	- BLEND. SM & SEBT	SBC	- BOSTON BLUE CLAY
SNHT	- BLEND. SNH & SEBT	SFFC	- FARGO CLAY
SEBT	- EAST BOSTON TILL	SAP	- ALASKAN PEAT
SNHS	- NEW HAMPSHIRE SILT	SI	- ARTIFICIALLY FROZEN ICE

FIGURE 3 - TYPICAL VARIATION OF SHEARING STRENGTH WITH TEMPERATURE (after KAPLAR (20))



LEGEND			
SNT	- BLEND, SH and SEBT	SYS	- YUKON SILT
SNHT	- BLEND, SNH and SEBT	SBC	- BOSTON BLUE CLAY
SEBT	- EAST BOSTON TILL	SFFC	- FARGO CLAY
SNHS	- NEW HAMPSHIRE SILT	SAP	- ALASKAN PEAT
SFS	- FAIRBANKS SILT	SI	- ARTIFICIALLY FROZEN ICE

FIGURE 4 - TYPICAL VARIATION OF
SHEARING STRENGTH WITH TEMPERATURE
(after KAPLAR (20))

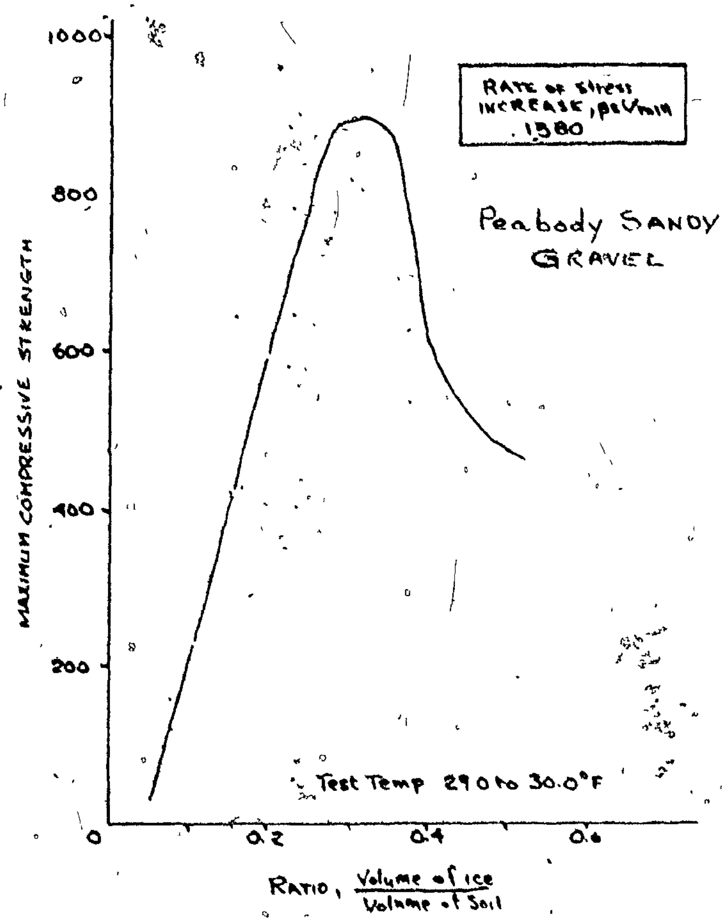


FIGURE 5 - TYPICAL STRENGTH VARIATION with ICE CONTENT (after KAPLAR (20))

and ice, can be examined as to strength and deformation characteristics.

The effects of the loading rate on frozen soil strength has been reviewed by Kaplar (20). The data from the American and Russian sources indicate that the strength of unsaturated frozen soils of normal unit weight always increases with the loading rate (see fig. 6).

It should be noted, however, that this trend would not continue indefinitely. As pointed out by Sayles (18), the phenomenon is probably limited by the brittle fracturing of the ice matrix at rates which would produce this phenomenon. Little effect was found on the short-term strength of soils tested with loading rates in the range of 200 to 1000 psi/min at temperatures in the area of -1 to 0°C. However, these loading rates are very high compared to those in most slope or foundation failures. If a relationship between strength and loading rate does exist, as proposed by Vyalov (21), and others (18,22), it would be much more practical to perform rapid testing and to extrapolate the strengths expected at whatever loading rate is encountered in the field conditions.

In analyzing landslide failures in the Mackenzie Valley, N.W.T., McRoberts and Morgenstern (23) observed that the long-term strength of permafrost soils appeared to be governed by frictional resistance. Sayles also observed this relationship for saturated frozen sand with a porosity of 37% or less (18). The long-term strength was thought to be a function of normal

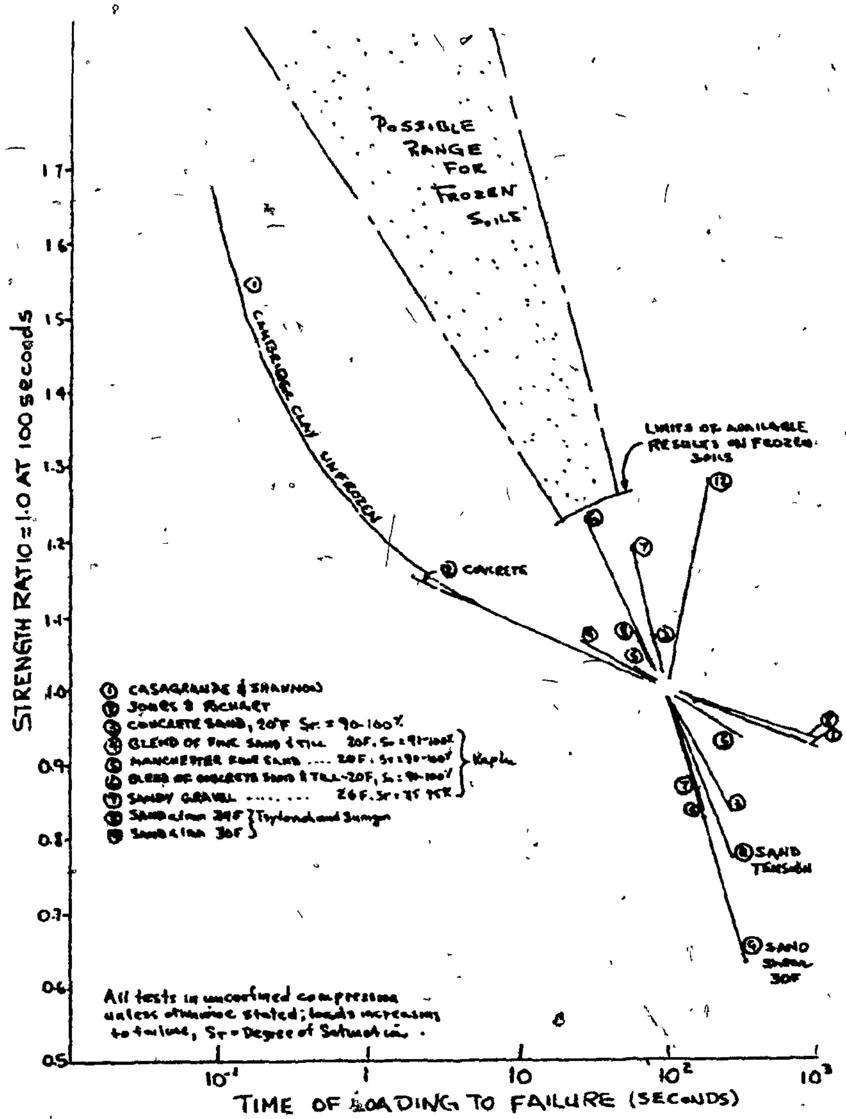
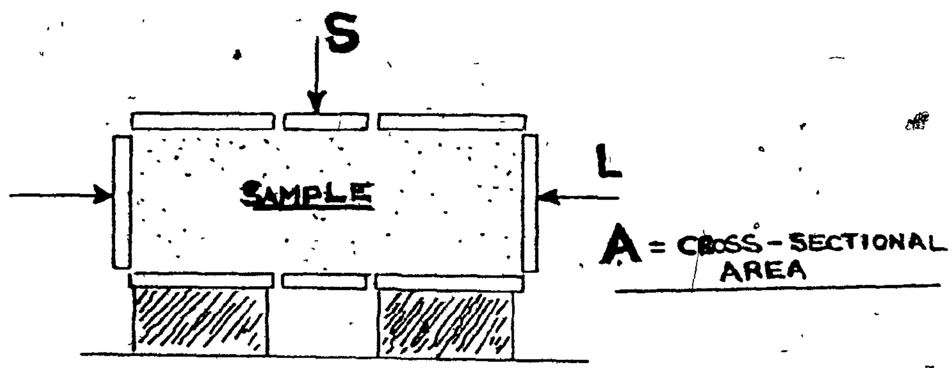


FIGURE 6 - STRENGTH RATIO vs TIME TO FAILURE
(after KAPLAR (20))

stress and the apparent angle of internal friction, which could be determined through triaxial tests on unfrozen material.

Geological structure is also to be mentioned as an important factor in the overall strength of the mass. Indeed, the nature of geological materials is such that the usual assumptions of homogenity and isotropy can rarely, if ever, be applied. Geological materials usually contain bedding planes, joints, shear zones, micro-cracks, and other discontinuities. The fabric or structures within the material probably govern the ultimate loading capacity and the mode of failure. It is therefore imperative that structural features be considered during the selection and preparation of laboratory specimens. The effects of sample size may thus be critical in determining the strength characteristics of natural permafrost. However, no such relationship has been published or proposed, to the author's knowledge.

Testing methods and apparatus are also important in considering the validity of the strength parameters thus determined. Triaxial direct shear with biaxial confinement, or torsional tests with axial compression, seem to be the most widely used methods in field rock mechanics and soil mechanics. From an engineering point of view, the direct shear test with normal pressure (fig. 7), is perhaps the simplest to perform. However, from a research point of view, various theoretical objections can be raised. Among these are the non-homogeneous distribution of stresses in the sheared sample, the indeterminancy of the stresses and strains within the sample, and the problem of



τ = SHEARING STRESS $= \frac{S}{2A}$

σ = CONFINING PRESSURE OR NORMAL STRESS $= \frac{L}{A}$

FIGURE 7 -DOUBLE DIRECT SHEAR TEST.

a fixed shearing surface (24). However, in an engineering study of directional properties, that is , properties influenced primarily by structure, some objections are invalid, and certain advantages of the method outweigh the apparent disadvantages. As listed by E.Z. Lajtai (25), the following features should be considered:

" 1) Failure through planes of weakness is an enforced failure and does not in general coincide with the orientation of shear fractures predicted from the Coulomb-Navier criterion. A similarly enforced failure occurs in the direct shear box (this is considered to be a disadvantage when testing isotropic materials).

2) In direct shear, one of the principal stresses is tensile. Such a state of stress cannot be reproduced in a conventional triaxial cell. Since failure in tension is quite common in geological materials (e.g. tension gashes associated with faults), the postulation of direct shear loading in nature is reasonable.

3) Unlike the triaxial test, the direct shear test allows the definition of the ultimate shear strength because the method permits shear deformation beyond the point of first fracturing.

4) In the direct shear test, the influence of the other planes of weakness is eliminated to a certain degree by the rigid confinement of all but a small portion of the test block. "

Moreover, from a cost point of view, the triaxial or torsional tests are much more expensive and time consuming.

Therefore, the direct shear test seems to offer the most practical solution to the experimental determination of the shear strength properties of permafrost, providing these with accuracies well within reasonable limits when compared to the heterogenous nature of natural permafrost.

2-4 Summary:

Many interrelated factors must be considered in determining the shearing strength of permafrost. The distribution of moisture in the various phases of the material will govern its strength to a great extent. The proportions of the various phases are governed by temperature and soil structure. In granular soils, unfrozen water content is considered negligible, and thus strength is directly related to total water content.

Effects of loading rate are not well understood; however, short-term strength determined in the range of 200 to 1000 psi/min can be used to fix one end of the scale. Long-term strength of frozen soil is thought to be frictional and can be determined using unfrozen samples.

The relationships of geological fabric to strength, although recognized as being possibly the most important considerations, have not been studied to any extent. It is thought, however, that large, natural samples with a greater amount of structure are more valid than small samples of reconstituted material.

The testing technique is itself a variable in the quantitative analysis of strength properties. The direct shear method with normal pressure although not the most theoretically accurate, seems to be the most practical for investigating directional properties of geological material.

III-EXPERIMENTAL INVESTIGATIONS

3.1 Sampling Program-Location and Geology:

A sampling program was undertaken to obtain suitable natural samples of permafrost. The location chosen was the Timmins #1 pit near Schefferville, Quebec, owned and operated by the Iron Ore Company of Canada. Schefferville is located about 700 miles northeast of Montreal. The mine site is approximately 12.5 miles northeast of Schefferville (see fig. 8).

The iron ore deposits in this area occur in the so-called "Labrador Trough", which consists of a 700 mile geosynclinal segment composed of tightly folded and faulted proterozoic sediments, volcanics, and intrusives (26). The rocks in the trough consist mainly of conglomerates, breccias, quartzites, shales and slates, dolomite, and iron formation.

The stratigraphic column of the deposits in the Timmins mine area is given in figure 9. The Middle Iron Formation of the Sokoman Iron Formation was chosen for sampling. This formation is readily differentiable given the color, which, although varying in places from purplish-red to a bluish-black, is characteristically blue. The texture is granular and porous. The unfrozen material can be described as a sandy silt.

The Middle Iron Formation is the chief ore-forming horizon. It is from 200 to 400 feet thick, and contains silica-iron oxide rich rock which has a high metallic lustre, due primarily to the presence of a large amount of blue hematite.

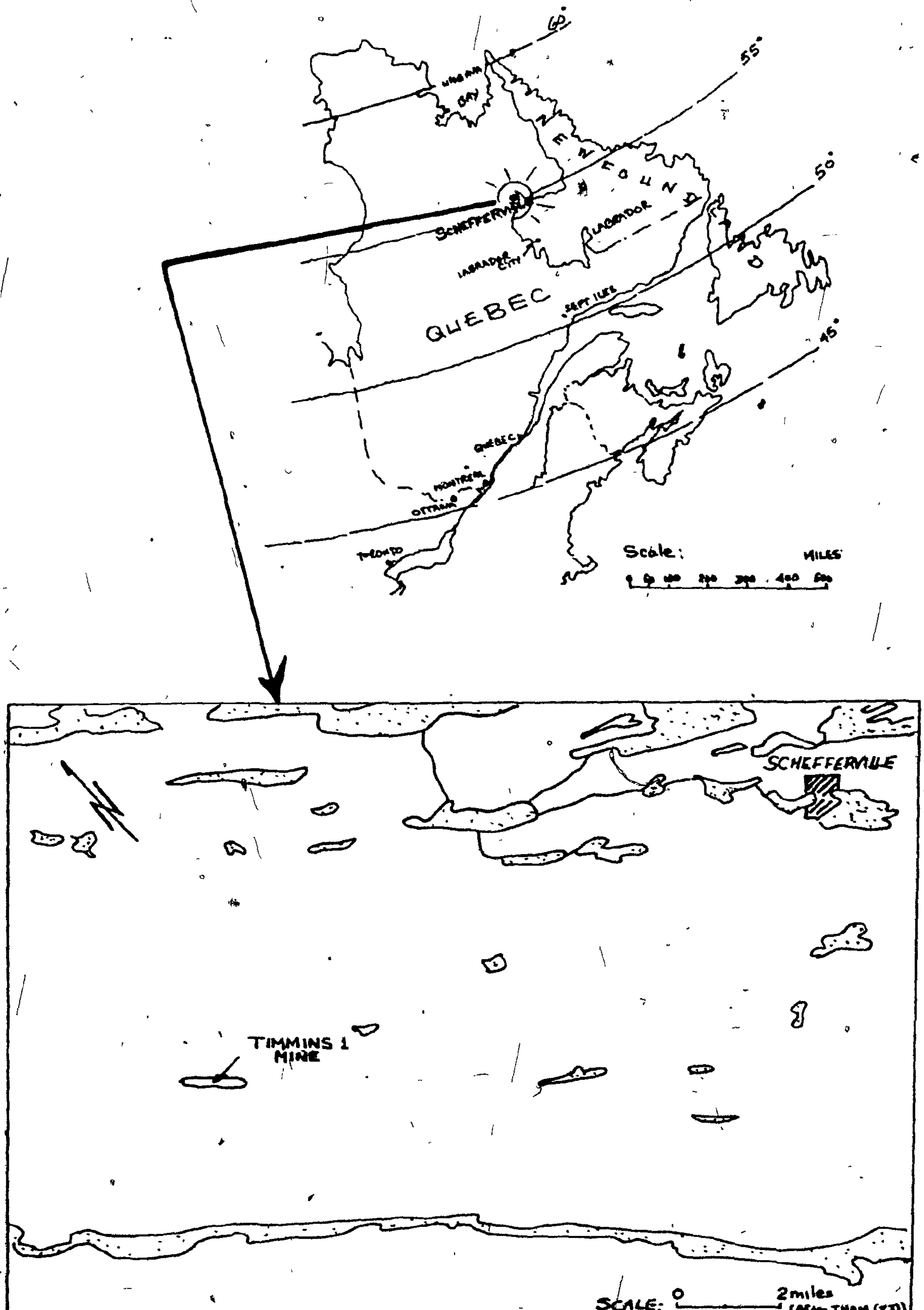


FIGURE 8 - LOCATION MAP
of TIMMINS PIT

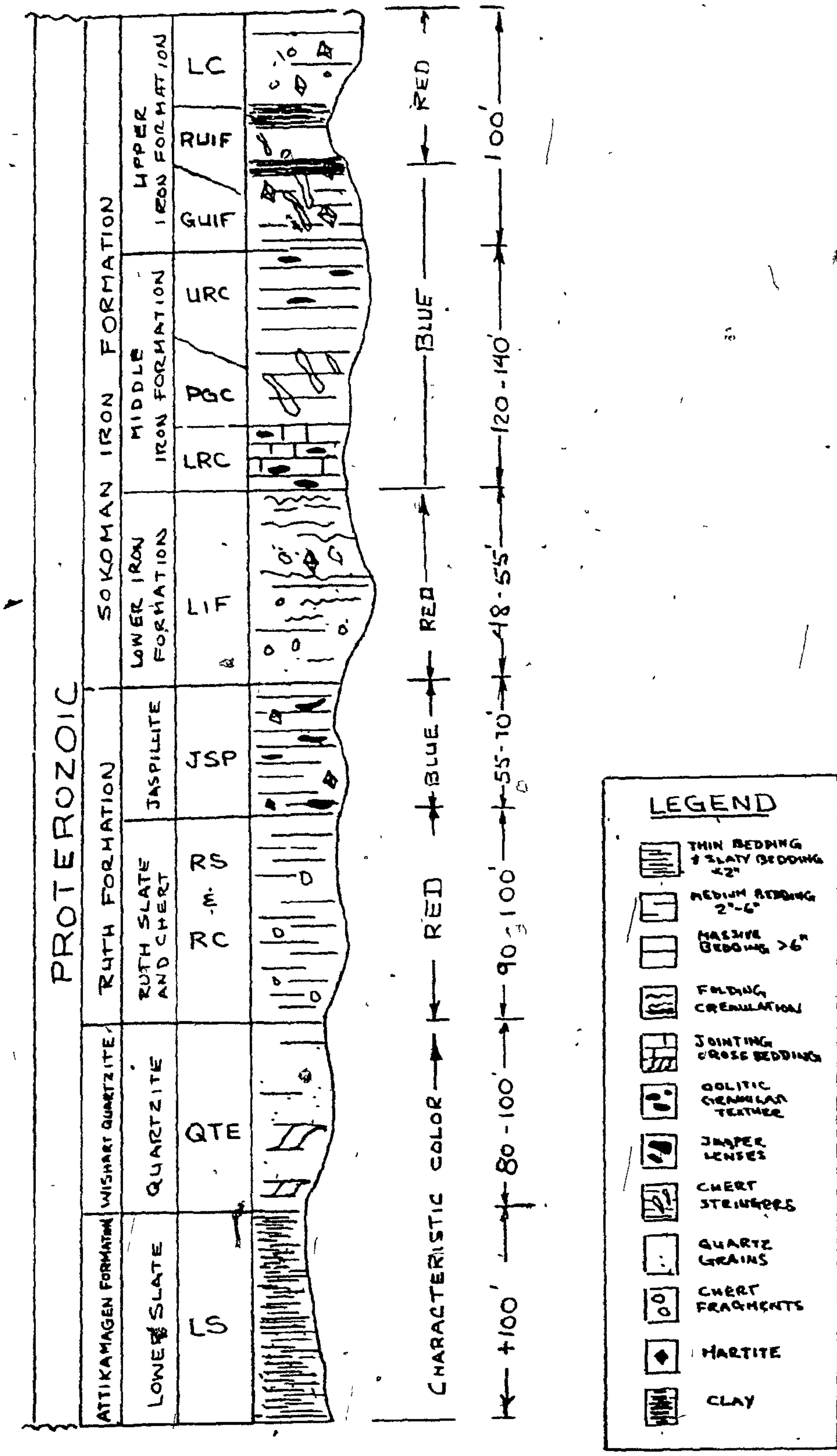


FIGURE 9 - STRATIGRAPHIC COLUMN - TIMMINS NO. 1 DEPOSIT

SOURCE: FIELD TRAINING PROGRAM, IRON ORE COMPANY OF CANADA Ltd

3.2 Sampling Program-Climatic Conditions and Permafrost Distribution:

Much information is available concerning the Schefferville area. The McGill Sub-Arctic Research Laboratory has been active in the region since the early 1950's, and much useful background information has resulted from the research conducted to date (27,28).

The mean annual air temperature at the Timmins 4 Permafrost Experimental Site is $-5.5^{\circ}C$, while the mean annual snowfall is 31.5 inches (13). The site is located a few miles north of the Timmins mine, the origin of the writer's samples.

In general, the area has a sub-arctic climate with cool summers and severe winters (27). The mean monthly temperatures at the Schefferville station range from about $54^{\circ}F$ in July to $-8^{\circ}F$ in January.

With the temperatures noted, a much greater amount of permafrost would be expected, as it is only maintained where the annual mean surface temperature is below freezing. The explanation lies primarily in the insulating effect of the snow and vegetation, which increases the expected ground temperature (29,13). The distribution is thus dependant on snow, vegetation, ground water, and the local relief.

In the Timmins mine open pit, values of ground temperature may be in the range of 27 to $29^{\circ}F$ (30).

These values were obtained during a project undertaken by I.O.C. in the summer of 1970. The two "Lifts", or working horizons, investigated revealed the existing permafrost conditions. A classification of permafrost was suggested, on the basis of such parameters as temperature, moisture content, ice content, and its form and lithology.

The MIF was described as being extremely dry and brittle. The pit faces were said to be frequently overhung. The material was said to vary locally from an "ice-bound material" to a "hard competent rock with little or no ice". Moisture contents of about 5% were noted.

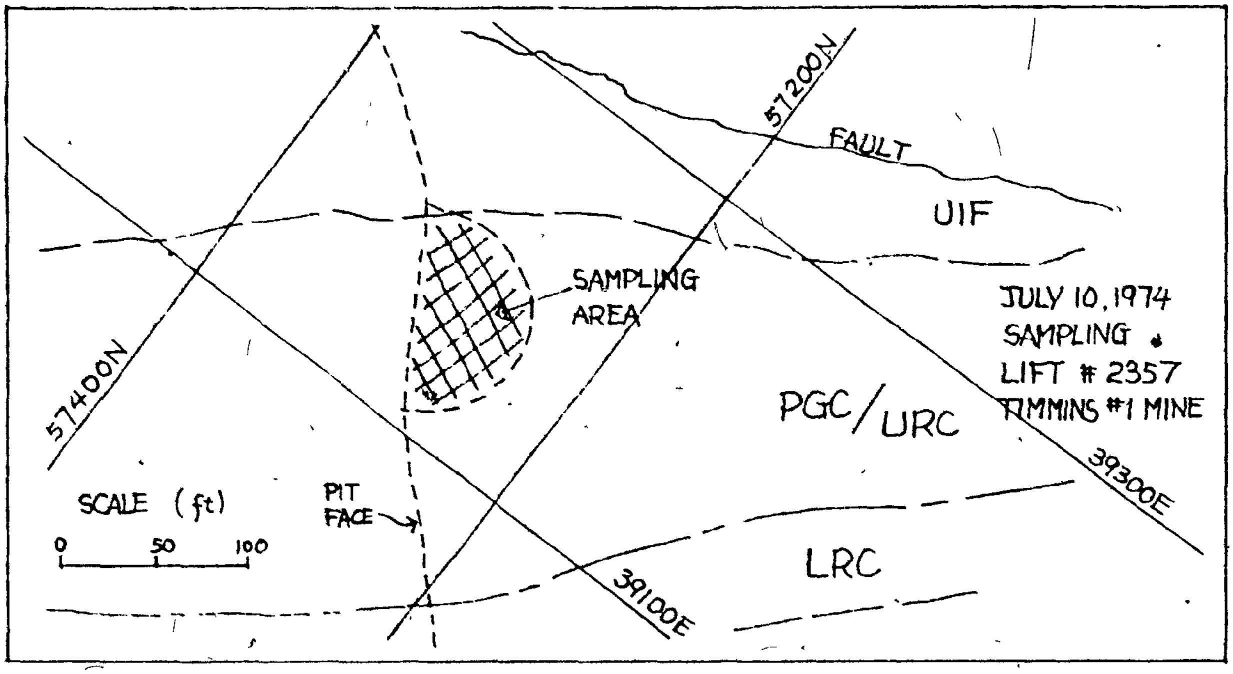
The horizons investigated were 190 and 130 feet above the horizon chosen in the sampling program for this project.

3.3 Sampling Program-Selection and Shipment:

The Timmins mine is worked as two separate sections, with pits being established at the north and south ends of the deposit. The south pit, located on the side of a ridge, contains permafrost. The north pit contains no frozen material. The causes of the difference are probably related to vegetation and snow cover conditions.

The samples were taken from two different locations at differnet horizons. The principal sampling concerned the recovery of samples immediately following a blast. Since the air temperature during the writer's visit was 45°F, any prolonged exposure of the materials lead to thawing and disintegration.

The sampling was done on Lift # 2357 and Lift # 2395. Small sketches of the locations are shown in figure 10. It should be



Note: for Stratigraphy see Figure 9

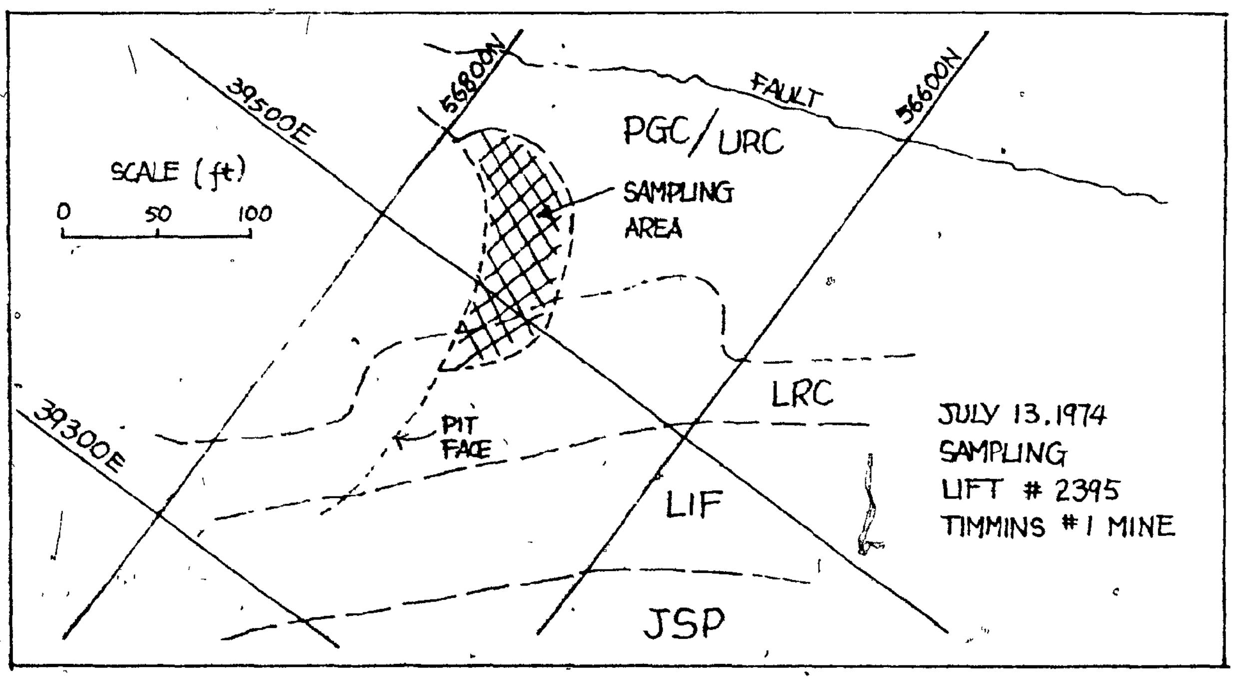


FIGURE 10 – GEOLOGY AND
LOCATION OF SAMPLING AREAS

noted that both sampling locations were in the PGC/URC of the Middle Iron Formation (see figure 9). The sampling was done on July 10 and July 13, 1974.

Within ten minutes after blasting, the sampling was started. The rough samples, approximately 9"x9"x8", were chiseled from larger pieces using a variety of hammers and chisels. These were then wrapped in commercially available polyethylene wrap, then with aluminum paper, and then were placed in plastic bags. The purpose of the aluminum wrap was to provide some insulation. The purpose of the plastic and polyethylene wrap was to avoid moisture loss. The samples were packed into three insulated ice chests, whose internal dimensions were 22"x11"x11". Two or three samples were placed in each. The ice chests were transported to a freezer unit in Schefferville for overnight storage. During storage the samples were packed in with ice packs; the chests were taped and secured with rope, and then shipped by air freight to Montreal. One shipment weighed 585 lb. and the second 500 lb. Upon arrival, a technician received the ice chests and transported them to the cold room laboratory at Mont St. Hilaire. After inspection, the samples were removed from the chests and placed in a freezer unit which was maintained at 25°F. A total of 185 samples were delivered and stored to await preparation and testing.

3.4 Testing on Unfrozen Samples:

While in Schefferville, the author conducted shear tests on thawed material obtained from the Middle Iron Formation. The samples were obtained from the same location selected for the samples which were shipped to Mont St. Hilaire.

The Geotechnical Engineering Section of the Iron Ore Co. of Canada permitted the author to use their 10 Ton capacity Wykeham-Ferrance shear box. The 12 inch shear halves were equipped with 2-1/8"Ø, 4"x4", and 6"x6" inserts; the shearing mechanism was adjustable to 42 various shearing rates, ranging from .03 in/min to .00008 in/min. The horizontal and vertical load capacities were both limited to 10 tons. (see figure 11)

The testing was done on a 6 inch sample packed into the shear box halves. The writer did not attempt to test an undisturbed sample, since the thawed material was too friable to permit the retention of structure. It would be possible, however, to obtain undisturbed samples by taking these frozen samples, cut to the dimensions of the shear box, and then permitting these to thaw while in the apparatus. As will be mentioned in the section on sample preparation, the most practical method for preparing the samples was found to be with the use of a portable grinder. A suitable environment must be maintained to permit sample preparation. The climate in the Schefferville area is such that, excluding the two summer months of July and August, the mean ambient temperature is sufficiently below or near the freezing point to permit the preparation of samples outdoors or in an

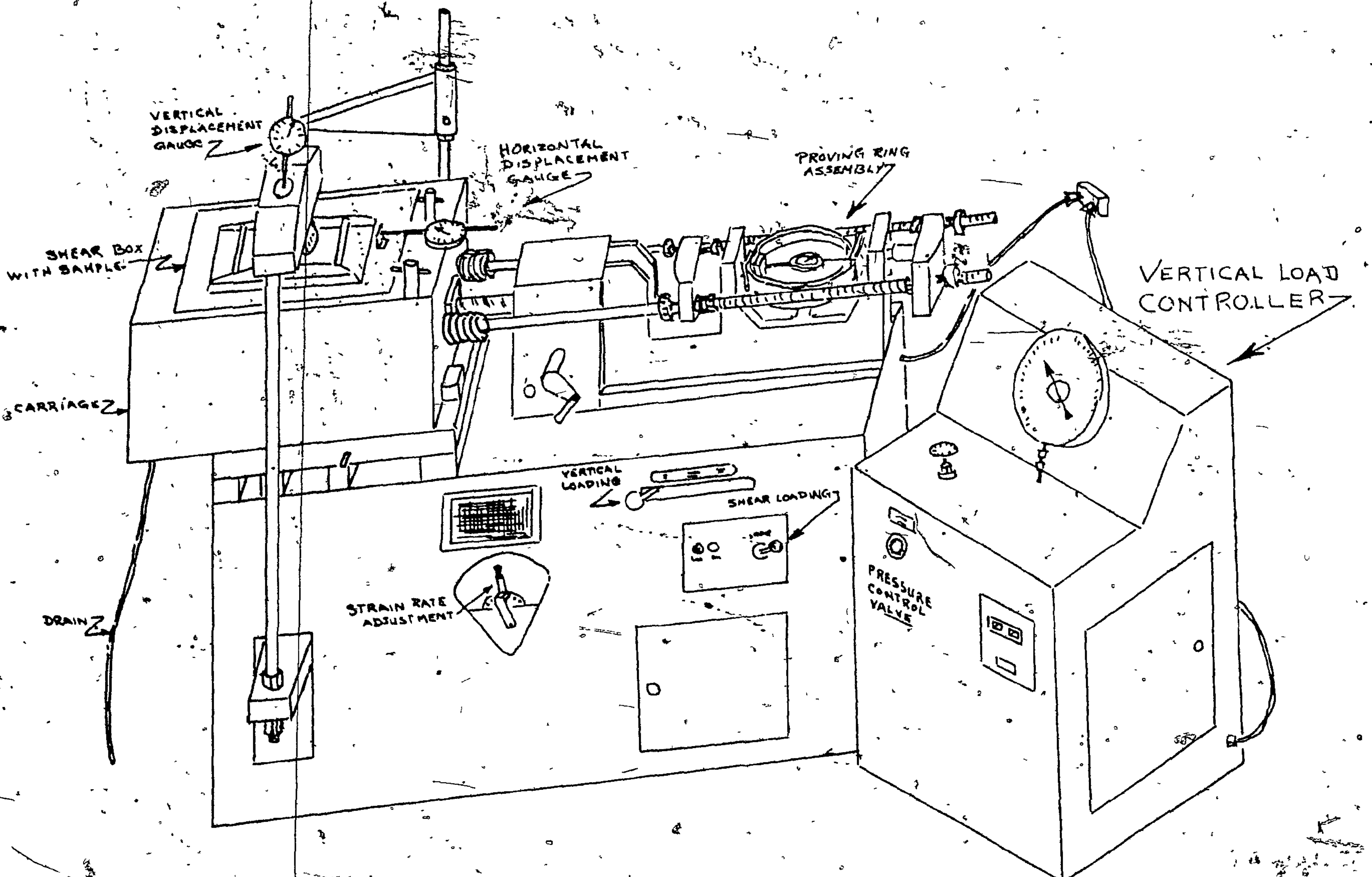


FIGURE 11 - WYKEHAM FERRANCE
WF 2550 10 TON SHEAR BOX

unheated building. By applying this method, a more accurate assessment of the natural material could be obtained.

The procedure used in testing was as follows:

1) setting the sample,
2) creating a separation of about 1/8" between the shear box halves,
3) applying a vertical load (100, 200, and 400 psi respectively),
4) allowing the sample to consolidate for 3 to 4 hours,
5) shearing the sample,
6) resetting the sample to vertical and applying a higher vertical load, consolidating, and reshearing.

The strain rate of .09 in/min was selected. The shear halves were submerged after the initial loading was applied, as is suggested by the proposed method for consolidated, drained direct shear testing of soils (6).

Displacement versus load data and maximum shearing strengths at the various applied normal stresses were measured. The shear tests, moisture content, and grain size analysis were obtained using standard procedures (5).

3.5 Cold Room Laboratory-Facilities:

The cold room laboratory is located at the Institute for Mineral Industry Research at Mont St. Hilaire, approximately 25 miles from Montreal, Quebec. The Institute is a part of the Department of Mining and Metallurgical Engineering of McGill University.

The cold room is a walk-in refrigerator, approximately 10 ft. wide, 11 ft. long, and 8 ft. high (in inside dimension). A detailed description is provided by S.M. Yap (14).

A Minneapolis-Honeywell resistance thermometer controller is used to control the temperature to within ± 1°F for the range of temperature for which the room has been designed, i.e. -50°F to +40°F. Two servoline recorders are used to record the temperature and humidity in the chamber. (see figure 12)

A small refrigeration unit, approximately 3 ft.x3 ft. by 4 ft. long was also used to store the samples. The unit, equipped with a continuous temperature recorder, has a temperature sensitivity of ±.1°F. (see figure 13)

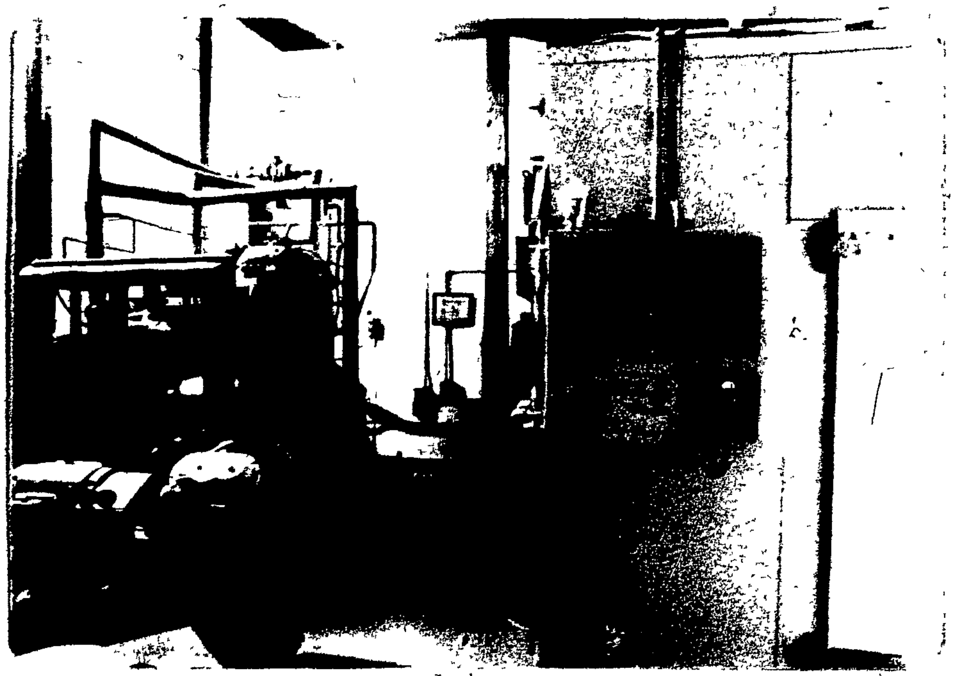


FIGURE 12 - COLD ROOM LABORATORY
POWER PLANT and TEMPERATURE CONTROLLER

FIGURE 13
TENNEY
REFRIGERATION
UNIT

3.6 Preparation of Natural Samples:

In this section, the problems encountered in the preparation of natural samples are reviewed, and recommended procedures for future work are given.

The samples required by the writer for testing were rectangularly shaped with approximate cross-sectional dimensions of 2" x 2", 4" x 4" and 6" x 6". Initial procedures involved rough cutting of the large sample blocks and trimming to the final dimensions. Various preparation techniques were attempted before the most practical procedures were established.

The hot wire technique of slicing was tried as a frist step. In this method, a high resistance wire was placed over a block with weights applied to either end; simultaneously, a current was passed through the wire. The method was rejected due to the length of time required per cut, and due to common occurences of broken wires. A reciprocating action of the wire resulted in faster penetration, but wires were soon abraded by the material.

The writer concluded that the hot wire technique might be useful for small samples of materials such as clay.

A reciprocating saw, or a mechanical hack-saw, was then tried. Once again, considerable abrasion resulted. Molybdenum tungsten blades were used at the rate of about one blade per 6" cut. Although a worn blade could be used, the cutting time became excessive. Another limitation was the size of the sample that could be accommodated in the saw.

Wedge-type cutting or breaking, using cold chisels and hammers, was also attempted. This method resulted in uneven surfaces. It was also time consuming, as a great deal of material had to be removed.

A tile saw fitted with a 6" blade was available to the writer. This would have been suitable for cutting the small 2" samples, however, it was inadequate for cutting the larger 4" and 6" samples. For these, a larger circular saw, with blades of at least a 20" diameter, would have been necessary.

A band saw was ultimately used for cutting the rough samples. Although the blades tended to wander during cutting, and uneven cuts resulted, the writer found the method to be suitable for rough cutting. While blades were worn out fairly quickly, cutting, in most cases, was not impeded. No significant differences were noted when wide and narrow blades were used, nor did the design of blade teeth appear to be significant. An average of one blade was used per sample. Wear to blade teeth seemed to vary with the hardness of the material being cut. Small inclusions of solid hematite impeded cutting significantly. Wear was also related to the pressure applied to the saw and to the uniformity of the material being cut.

In cutting the 2" samples, sufficient alignments were maintained to produce test samples within acceptable tolerances. After cutting the larger samples, however, further preparation was required. A portable grinder was used to bring the large samples to acceptable final dimensions.

A hand-held grinder, with a 4" circular abrasive blade, was used. Samples were secured in a vise and the upper surface ground to flatness. A plane surface was used to detect unevenness. The remaining faces of the sample were then ground.

Some skill was required for grinding since material, once removed, could not be replaced. Overly ground samples would have to be discarded. Some thawing of the surfaces resulted from the grinding; however, in the case of the 4" and 6" samples this was thought to be negligible. The grinding wheel used was not replaced, although it was reduced by about one inch in trimming the samples. Therefore this method is fairly economical.

It is suggested that an improvement to the procedure would result from a mounting of the grinding wheel into a sturdy frame. Alternately, a grinder which could accomodate large, movable samples could be used. Either of these, together with initial rough cutting of the samples, would seem to be the most economical and practical methods of sample preparation. For large, blocky materials, a circular saw would be the only alternative. Abrasive, rather than diamond blades, are indicated for non-uniform materials. For rocks, a diamond blade is necessary.

After preparation, the samples were wrapped with thin polyethylene plastic and placed in plastic bags, which were secured to produce an air-tight seal. This was necessary in order to prevent a loss of moisture through surface sublimation. The samples were then labelled and stored in a small refrigeration unit.

3.7 Preparation of Remolded Samples:

The writer prepared a number of remolded samples, in order to compare the effects of re-molding on sample strength. As mentioned earlier, most studies on the mechanical properties of permafrost have been done using reconstructed material. In this process, geological strucure is destroyed, and what remains is a more or less homogeneous mass, which may not be representative of the original material. To determine quantitatively the effects of geological strucure on the strength characteristics of the natural permafrost samples, remolded samples were prepared. These samples were made from the fragments of the sheared natural samples. After the initial shear tests, the fragments were collected and placed in sealed plastic bags. This ensured that the material would thaw without a loss of moisture.

After thawing, the material was placed in a plastic trough and mixed so that a relatively homogeneous sample would be produced. A very small amount of distilled water (20 ml) was introduced to compensate for possible evaporation, and other, losses.

Wooden molds, used for remolding the samples, were assembled as shown in figure 14. The sides of the boxes were coated with petroleum jelly in order to facilitate disassembly after remolding.

Packing of the thawed material into the boxes was done in 2 inch lifts. Material was placed in the box and packed manually. During remolding, the boxes were covered in order to retard sublimation.

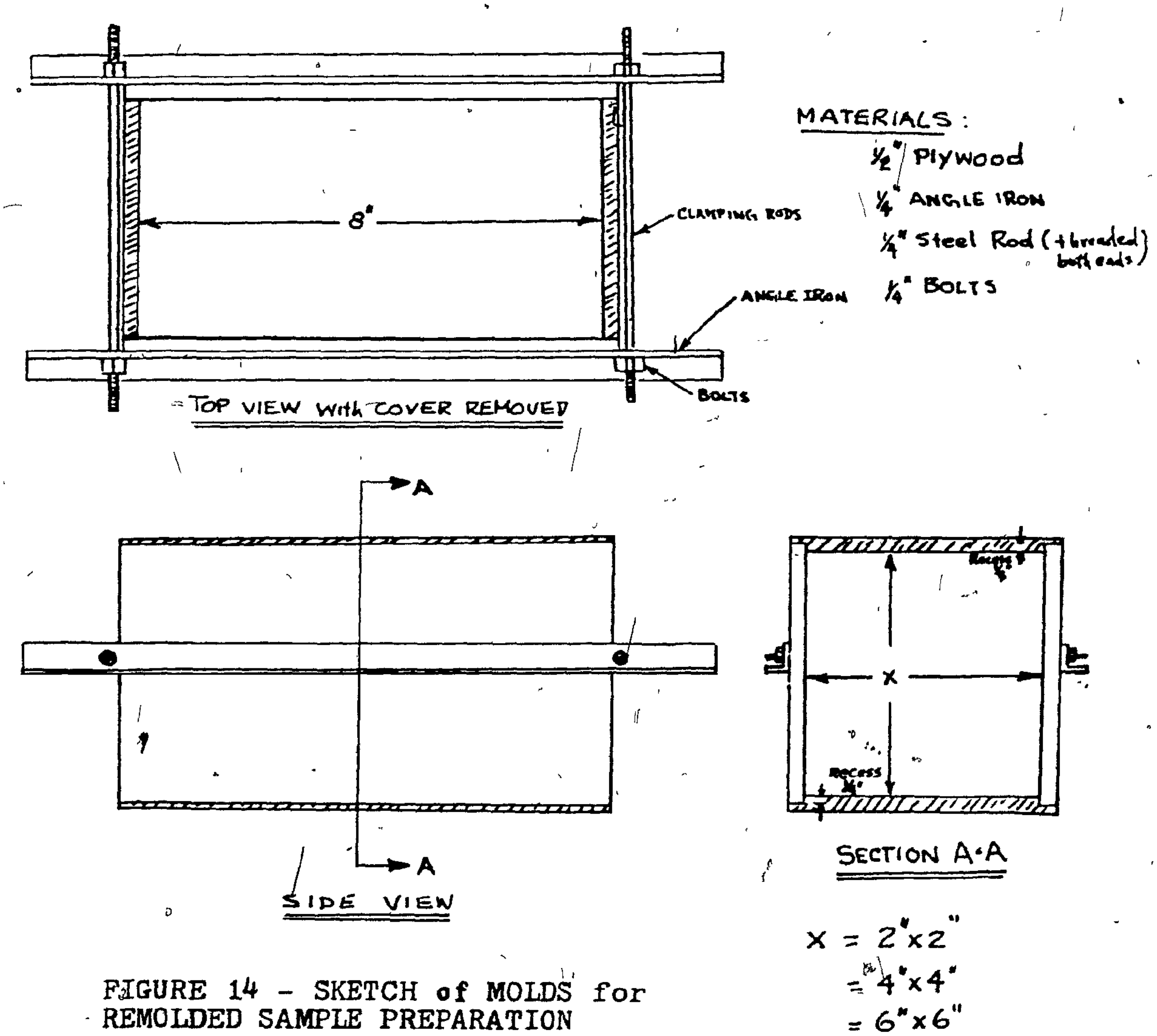


FIGURE 14 - SKETCH of MOLDS for REMOLDED SAMPLE PREPARATION

The filled molds were then placed in the small freezer unit (at 25°F) and the contents allowed to freeze. A minimum freezing period of 5 days was used.

No apparent volume changes occurred during the freezing process. It could be concluded, therefore, that the material was not saturated and that it probably would not be susceptible to heaving.

Remolded samples were tested under the same testing conditions as were applied to the original samples from which these originated.

3.8 Equipment Design:

A high-capacity shearing apparatus was designed by the author and built under his supervision at the Institute for Mineral Industry Research. The unit was designed to accomodate large samples (up to 6"x6"), and to permit the application of biaxial loading to 25 tons.

Mechanical drawings of the shearing apparatus are included as Appendix A. A schematic in figure 15 is given to illustrate the various capacities and capabilities of the apparatus.

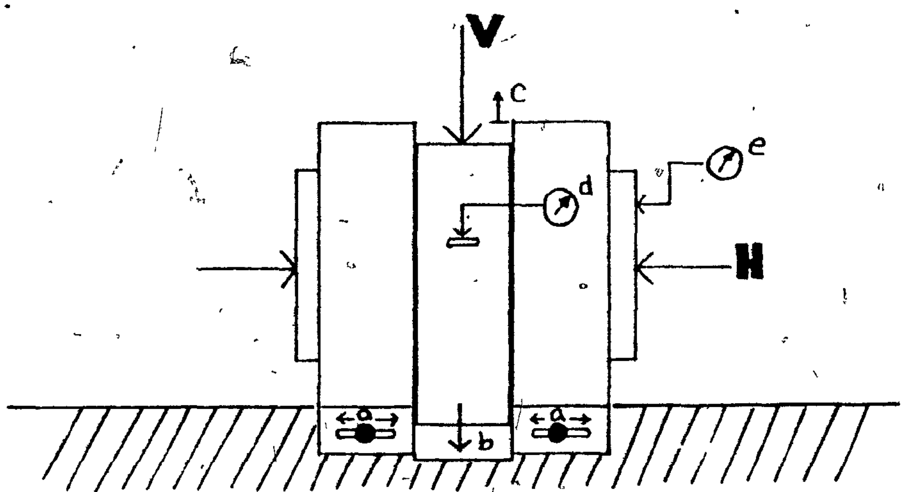
The machine enables double direct shearing. This configuration, as opposed to single direct shearing, avoids eccentric loading and enables a greater shearing area, since it involves two faces.

From an analysis of the results obtained for a similiar material tested by Yap in 1973 (14), the estimated loading capacities of the testing machine were calculated.

It was decided that, if confinements up to 500 psi were to be considered, a vertical loading of 100T hydraulic cylinder would be required to apply the direct shearing loads. Two 25 ton capacity hydraulic cylinders were used to apply horizontal confinement (figure 16).

Loading was applied hydraulically using hand pumps. Loads were determined from pressure gauges fitted to the lines (fig.17).

After testing, the gauge readings (in psi) were converted into applied load. The calibration curves determined using a proving ring are given in Appendix B.



V = maximum vertical load = 100 T

H = maximum horizontal load = 25 T

a = adjustable gap dimension - to 2"

b = maximum downward displacement = 2.5"

c = maximum upward displacement = 1"

d = vertical displacement gauge

e = horizontal displacement gauge

FIGURE 15 - SCHEMATIC
100^T SHEARING APPARATUS

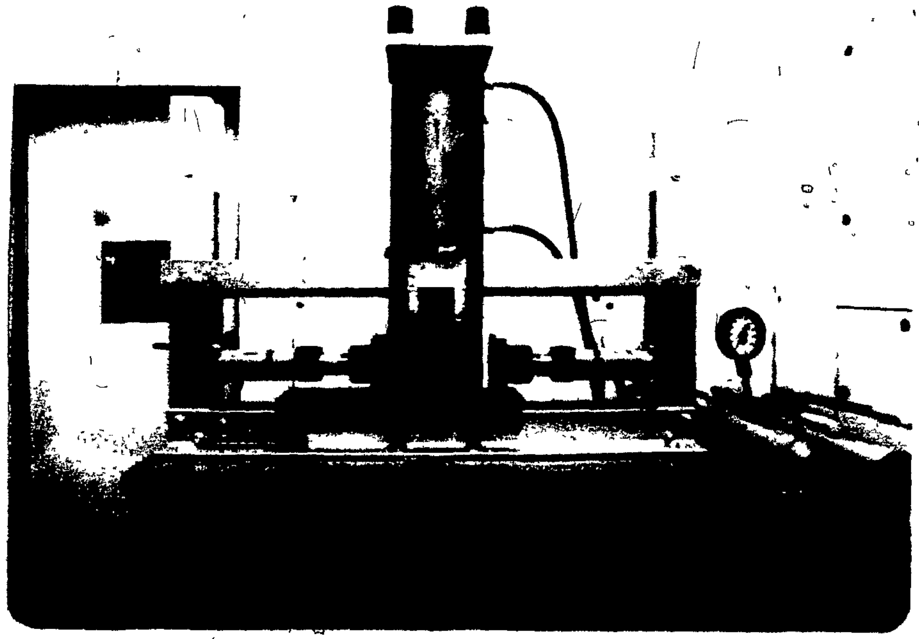


FIGURE 16 - DIRECT SHEARING APPARATUS
GENERAL VIEW

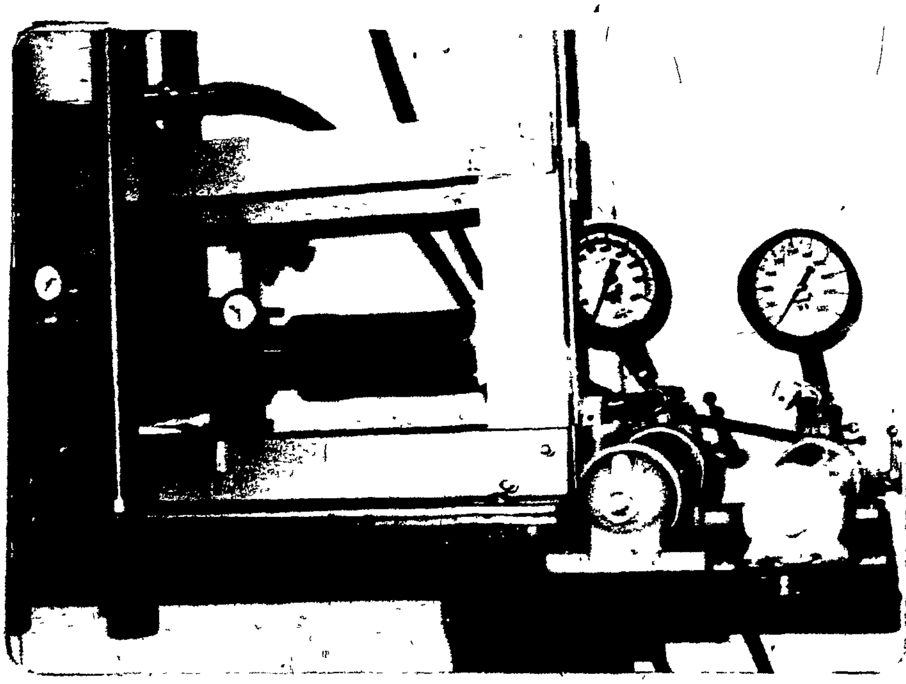


FIGURE 17 - DIRECT SHEARING APPARATUS
PUMPS and PRESSURE GAUGES

The shear boxes were made from one inch cold rolled steel. The two outside sections were adjustable through a sliding platform to which they were attached.

In the design, the writer established that the central section of the shear box could not be displaced more than $2\frac{1}{2}$" downwards and 1" upwards.

One of the 25^T hydraulic cylinders was hinged to permit easy access for loading and unloading specimens from the shear boxes.

Inserts for the 6" x 6" shear boxes were also assembled. These were 2" x 2" and 4" x 4" in dimension. The inserts for the middle box could be secured in place by means of a bolt threaded through the three boxes on either side of the box. The two side shear boxes have inserts with outside flanges to restrict their inward movement. (see figure 18)

Vertical movement during shearing was detected using a magnetically mounted displacement gauge. The gauge was accurate to within .001". (see figure 19)

The shearing apparatus was tested to its design specifications and found to operate efficiently and safely.

FIGURE 18 - DIRECT SHEARING APPARATUS
INSERTS and PLATENS

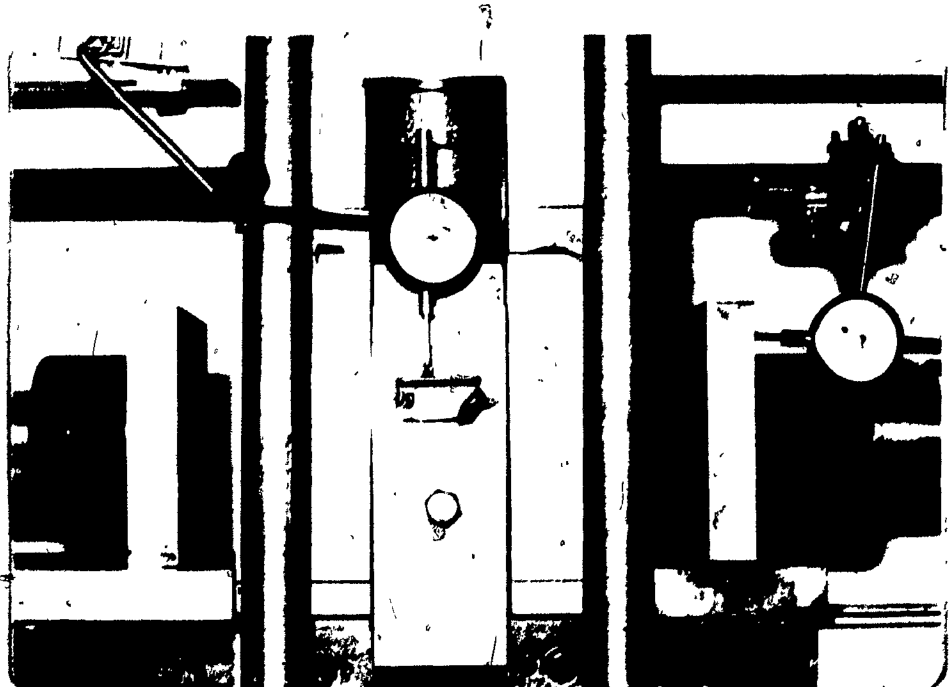


FIGURE 19 - DIRECT SHEARING APPARATUS
VERTICAL DISPLACEMENT GAUGE

3.9 Testing Procedure:

The description of the testing procedure outlines the methods used to produce the data given, aiding further research with the apparatus.

After unwrapping, the samples were measured using a vernier caliper. The accuracy of the measurements was affected by both the amount of pressure exerted on the caliper and the smoothness of the sample. Therefore, these measurements were approximated to the nearest .005 inch. In some cases, variations of up to ±.01 inch were noted. A minimum of three readings for each dimension of each sample were taken. The averages were used in calculating the areas.

In preparing the shearing apparatus, the shearing boxes were aligned with a separation of 1/8 inch between each pair. The adjustable horizontal ram was pivoted out of the way and the sample was then inserted.

After determining the cross-sectional area, the pressure necessary to maintain the desired confinement was determined. normal pressure of 100 psi and 50 psi were used, as well as tests without horizontal confinement. The sample was allowed to settle under this applied load.

The vertical ram was lowered until contact with the specimen was detected by an increase in the load. This load was then removed and the vertical displacement guage read and recorded as the initial reading. The vertical loading was then applied, the confining pressure being continuously adjusted to maintain a constant pressure.

As the shear loading was applied, vertical shear displacement readings were taken at regular increments of line pressure, varying from 50 psi for the smaller size samples to 250 psi for the larger samples. These were recorded and later tabulated.

As the loading was applied, it was noticed that the sample would creep somewhat. A steady loading rate was maintained, however, until the sample failed. Sharp brittle fracturing was noticed only in some cases of unconfined shearing. The maximum shearing stress applied was recorded.

To remove the sample, the middle box was raised, the detachable ram was pivoted out, and the line pressure disconnected. Pressure was applied to the other ram and the sample was removed. The boxes were then cleaned and readied for the next sample. The loading, testing, and unloading operation took approximately 45 minutes per sample, thus being particularly suitable for commercial testing.

After the shearing tests, the remaining fragments were used in determining density and moisture content, as well as in grain size analyses. Density was particularly difficult to ascertain in that the volume of the frozen samples could not be obtained using conventional water displacement methods. An improvised sand box method was used. A fine sand, rather than water, was used to displace the volume of the sample. The method, with sample calculations, is described in Appendix C. Where the samples were found to be sufficiently regular, their volumes were determined by means of a vernier caliper. A beam balance was used to measure the weight of each sample to within .01 gm.

The moisture contents and grain size analyses of the samples were obtained using conventional techniques as outlined in Lambe (5). Three determinations for density and moisture content were done for the six inch samples; two determinations for the four and two inch samples.

IV - RESULTS and ANALYSES

4-1 Introduction:

The statistical variabliity of physical and mechanical properties must always be considered when testing geological materials. In many cases, a sufficient number of samples is unavailable due to logistic and economic restraints. The design engineer must therefore make the best use of the values available to him, bearing in mind the limitations of his results. It is with respect to this concept that the following results are analyzed.

The present study made use of 1085 lb. of natural permafrost material, which provided three 6" x 6" samples, five 4" x 4" samples, eight 2" x 2" samples, and numerous samples remolded from thawed fragments. The results of the tests examine the relationships between:

a) sample size versus material strength and deformation characteristics;

b) normal pressure versus material strength;

c) strength of remolded material versus strength of natural material.

For comparison of deformation and shear strength properties, tests were also conducted on an unfrozen sample of geologically similar material.

Except for the unfrozen sample tested at Schefferville, which used the facilities of the Iron Ore Company of Canada, all shear testing was done using the 100^T shearing apparatus outlined in Section 3-8.

4-2 Unfrozen Sample - Schefferville Tests:

A Wykeham Ferrance shear box, shown in figure 11, was used to establish the shear strength parameters of unfrozen MIF. The procedure and test conditions are described in Section 3-4.

This material was geologically similar to the samples tested in the cold room at Mont St. Hilaire. All samples were taken from the same general area (see Section 3-4), and were visibly similar in texture and color. Grain size analyses were performed on all material. The results are tabulated and contained in Appendices E and F. From summary curves shown in figure 20, it can be seen that the tests on the Schefferville sample established its similarity to the samples subsequently tested.

The Schefferville tests were carried out using the procedures and test conditions described in Section 3-4. Load versus deformation data is tabulated in Appendix E; summary curves are shown in figure 21. It can be noted that the material behavior changes from visco-elastic to visco-plastic at a shear displacement of approximately 0.3 inches. This seems to be independant of normal confinement.

The increases in peak shear strength values with increasing normal stress are shown in figure 22. The angle of friction is 29^{o} with a negligible cohesion value.

The moisture content of the sample was determined to be 8.7%, being typical of the subsequently tested permafrost samples.

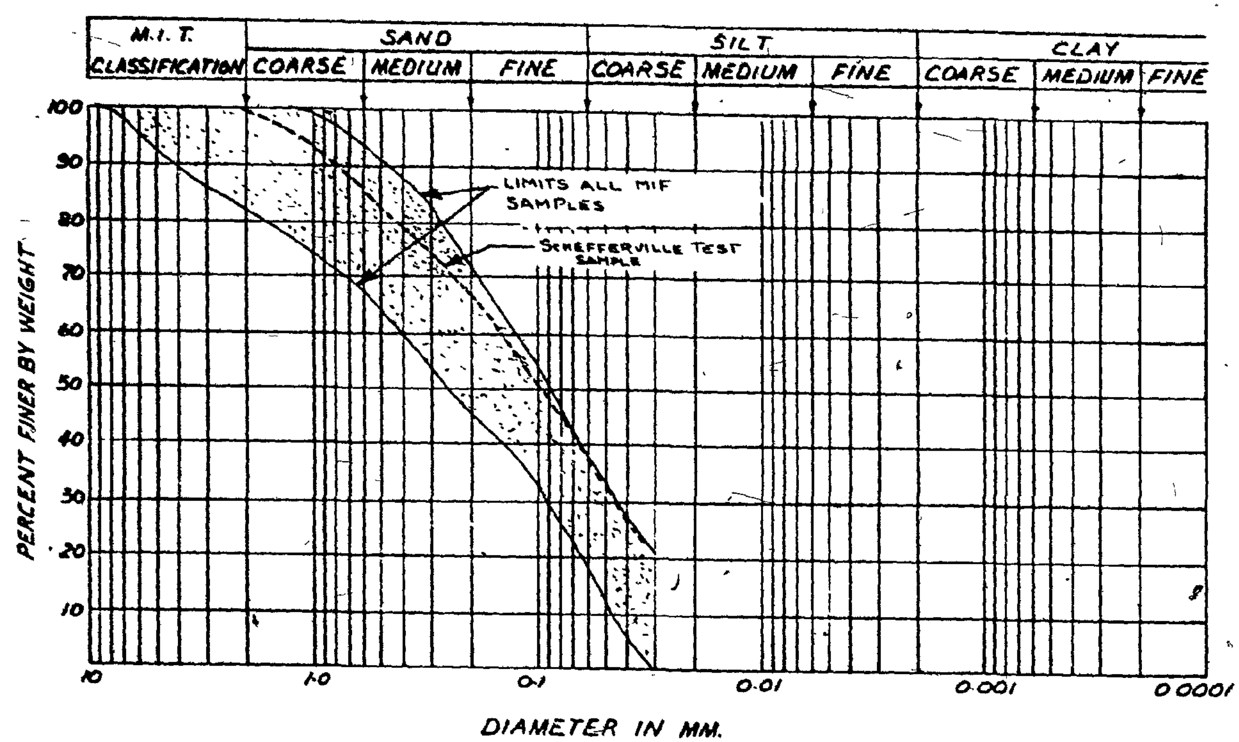


FIGURE 20 - SUMMARY of GRAIN SIZE DISTRIBUTION CURVES

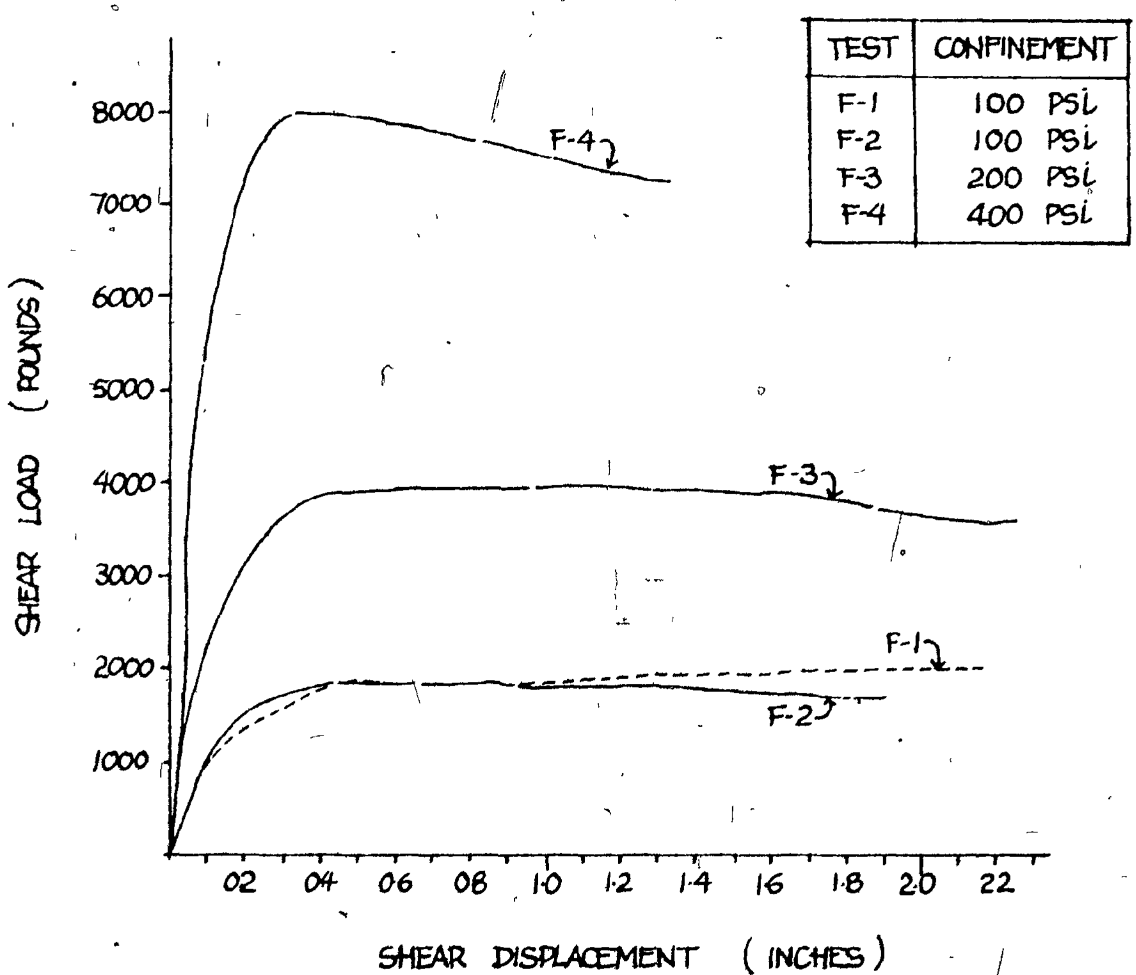


FIGURE 21 - LOAD - DISPLACEMENT CURVES - SCHEFFERVILLE TESTS -

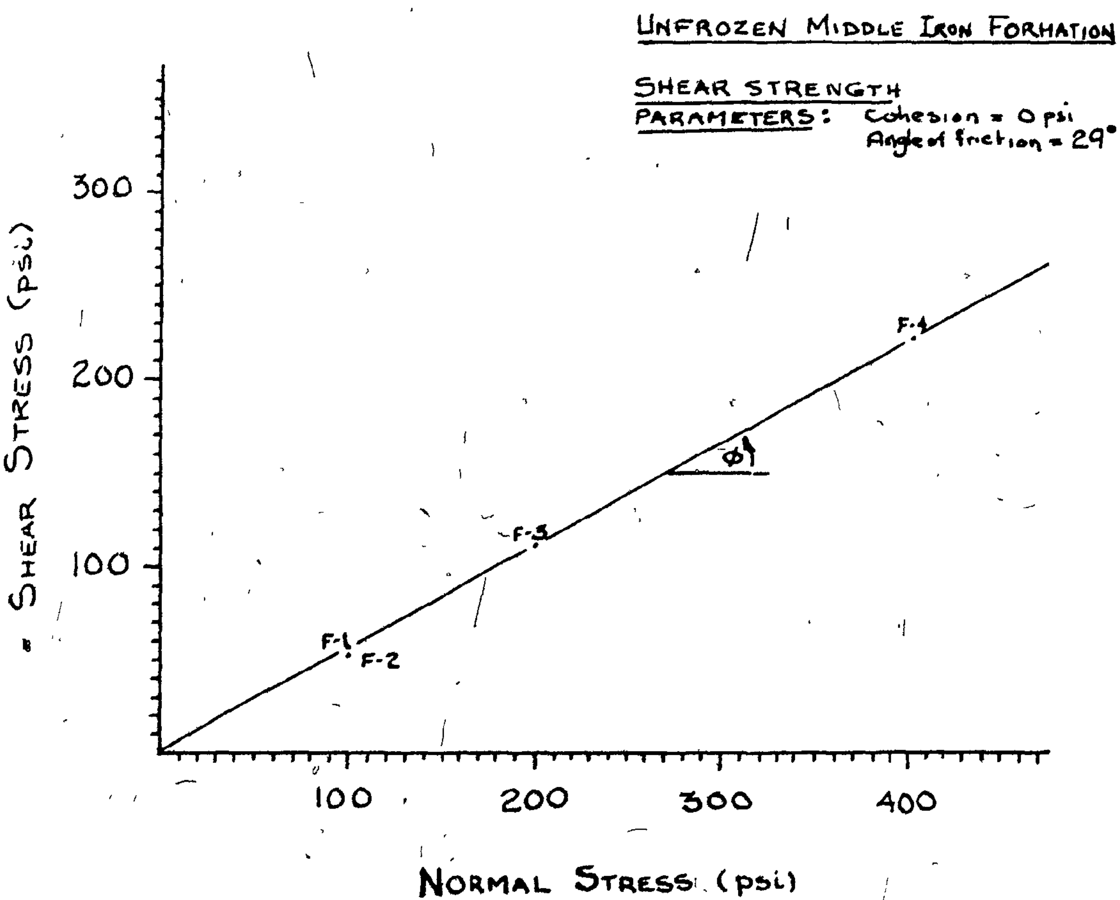


FIGURE 22 - SHEAR STRESS versus NORMAL STRESS - SCHEFFERVILLE TESTS

4-3 Permafrost Samples:

All samples were visibly similar in texture and color. Determination of grain size distributions and densities confirmed this similarity; however, the moisture contents showed a wider range of values.

Results of the grain size analyses are given in Appendix E. A summary of the data showing the limits within which the MIF falls is given in figure 20. The material can be seen to be well graded, having uniformity coefficients between 5 and 9.

Moisture contents and densities are reported in Appendix D, and summarized in Table 1 . The samples are seen to have an average moisture content of 8.9%, and an average density of 3 gm/cc.

Shear test data for natural samples are given in Tables D-1 to D-14 of Appendix D. On examining the relationships between the shearing stress and vertical displacement, as summarized in figure 23, it is noted that all the natural samples tended to exhibit similar behavior. The 2" samples occupy the upper series of curves, while the 4" and 6" samples show more displacement per unit of stress and occupy the lower series of curves. With the exception of SAM 4-4, the 4" and 6" samples showed much greated linearity than did the 2" samples.

In figure 23, two characteristic slopes are evident; one parallel to the lower series of curves, and one parallel to

TABLE 1 - MOISTURE CONTENTS and DENSITIES
NATURAL PERMAFROST

SAMPLE	MOISTURE CONTENT %	DENSITY gm/cc
SAM 1-6	2.3	3.0
SAM 2-6	7.3	3.15
SAM 3-6	10.2	3.3
SAM 1-4	4.9	3.3
SAM 2-4	10.0	3.2
SAM 3-4	10.3	3.3
SAM 4-4	10.3	3.2
SAM 5-5	4.1	3.3
SAM 1-2	10.3	2.5
SAM 2-2	11.9	3.0
SAM 3-2	11.6	3.1
SAM 4-2	11.2	3.1
SAM 5-2	9.2	3.3
SAM 6-2	6.2	3.2
SAM 7-2	11.7	3.1
SAM 8-2	5.2	3.0

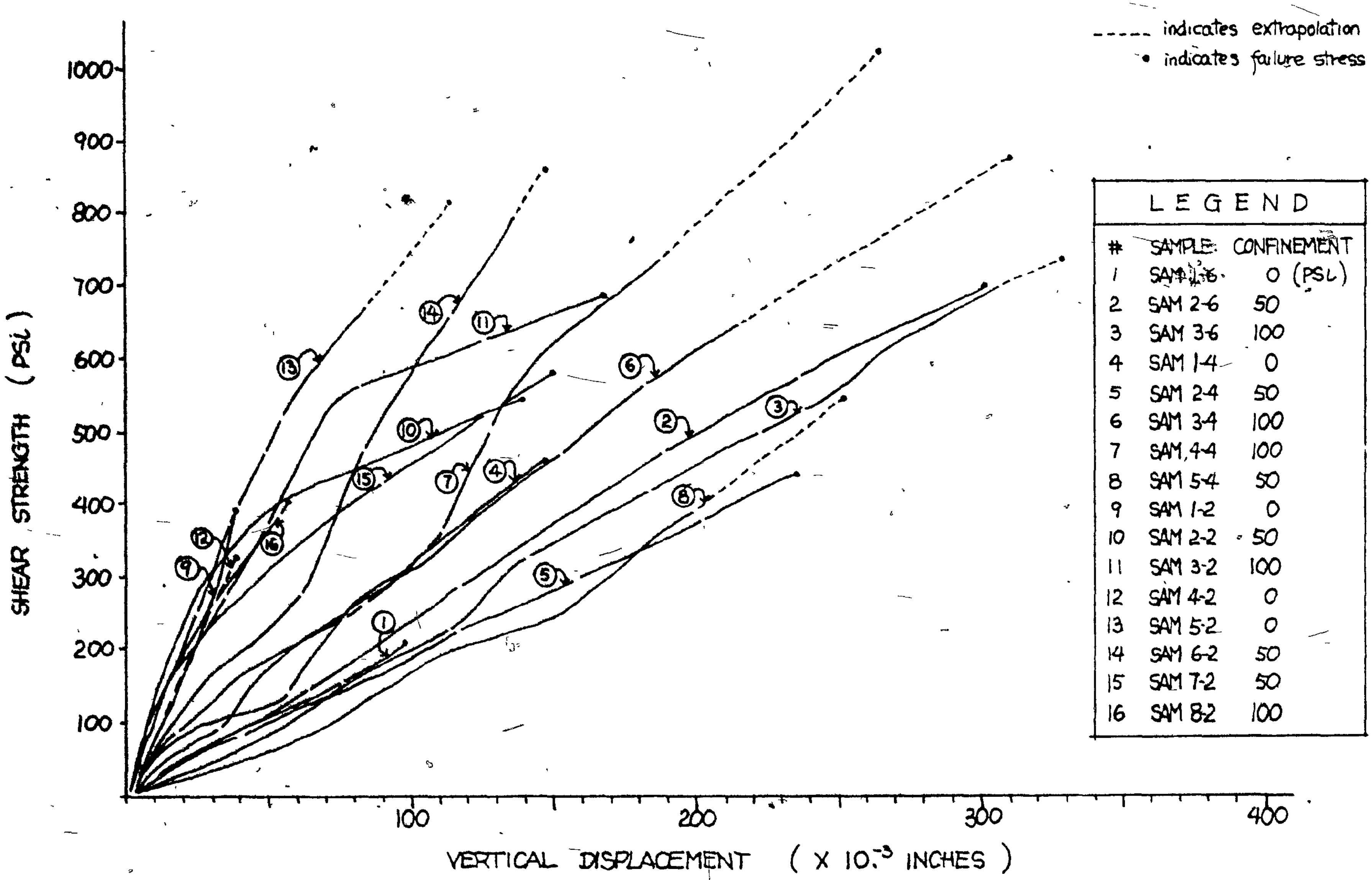


FIGURE 23 - SHEAR STRESS - DISPLACEMENT
CURVES - NATURAL PERMAFROST

the upper series of curves. Only one of the 4" samples (SAM 4-4) exhibits both slopes. Four of the eight 2" samples (SAM 6-2, 3-2, 2-2, 7-2) also show this behavior in their deformation characteristics. The explanation for this seems to be that, given that all samples had similiar grain size distributions (see figure 20), inclusions on the shear plane have a greater effect on the shear stress of smaller samples.

Although the chances were reduced, the 4" samples were still prone to this problem. As illustrated by the deformation curve for SAM 4-4,* it would seem that the shearing plane encountered large inclusions at 0.070 inches vertical displacement and again at 0.12 inches vertical displacement, giving rise to the sudden increase in slope. This problem can be circumvented by increasing the gap dimension between the shear box halves. However, this is not always satisfactory, as the size of inclusions may be such that an excessive gap would have to be left. This would produce eccentric loading problems. As well, the largest particle size must be known before testing, which, in the case of natural samples, is impossible. If, however, the sample homogeneity is such that the size of the largest particle can be determined from geologically similiar material, the gap can be adjusted accordingly.

Since shear failures in the field occur on large planes, it is safe to conclude that the deformation characteristics illustrated by the lower series of curves is probably more accurate than results obtained from the 2" samples.

The brittle behavior of the samples is evident. In most cases, excepting where changes in slopes were experienced, the samples broke abruptly after a linear build-up in stress. This is as expected, given the rates of loading used, which were above the ductile to brittle transition zone discussed in Section 2-3.

The range of shearing strength, with confinement pressure for the samples tested, is shown in figure 24. There is considerable scatter of data, as could be expected from any natural geological material. Factors influencing this scatter could include varying moisture content and varying geological structure of the material. For example, the low shear strength value obtained for SAM 1-6 could be due to its relatively low moisture content.

The number of samples tested should be taken into account when interpreting the data to obtain shearing parameters for use in design work. Working design values can be obtained by grouping all samples together and taking average values at each confinement. As shown from figure 25, a cohesion of 435 psi and an angle of friction of 83° were determined. The cohesion value arrived at is consistent with results reported by M. Yap (14) in his tests on MIF. Values of 355, 368 and 400 psi were listed. The testing was done using 1" cubes at 28°F, with a loading rate of 286 psi/min.

The angle of friction of 83° appears high when compared

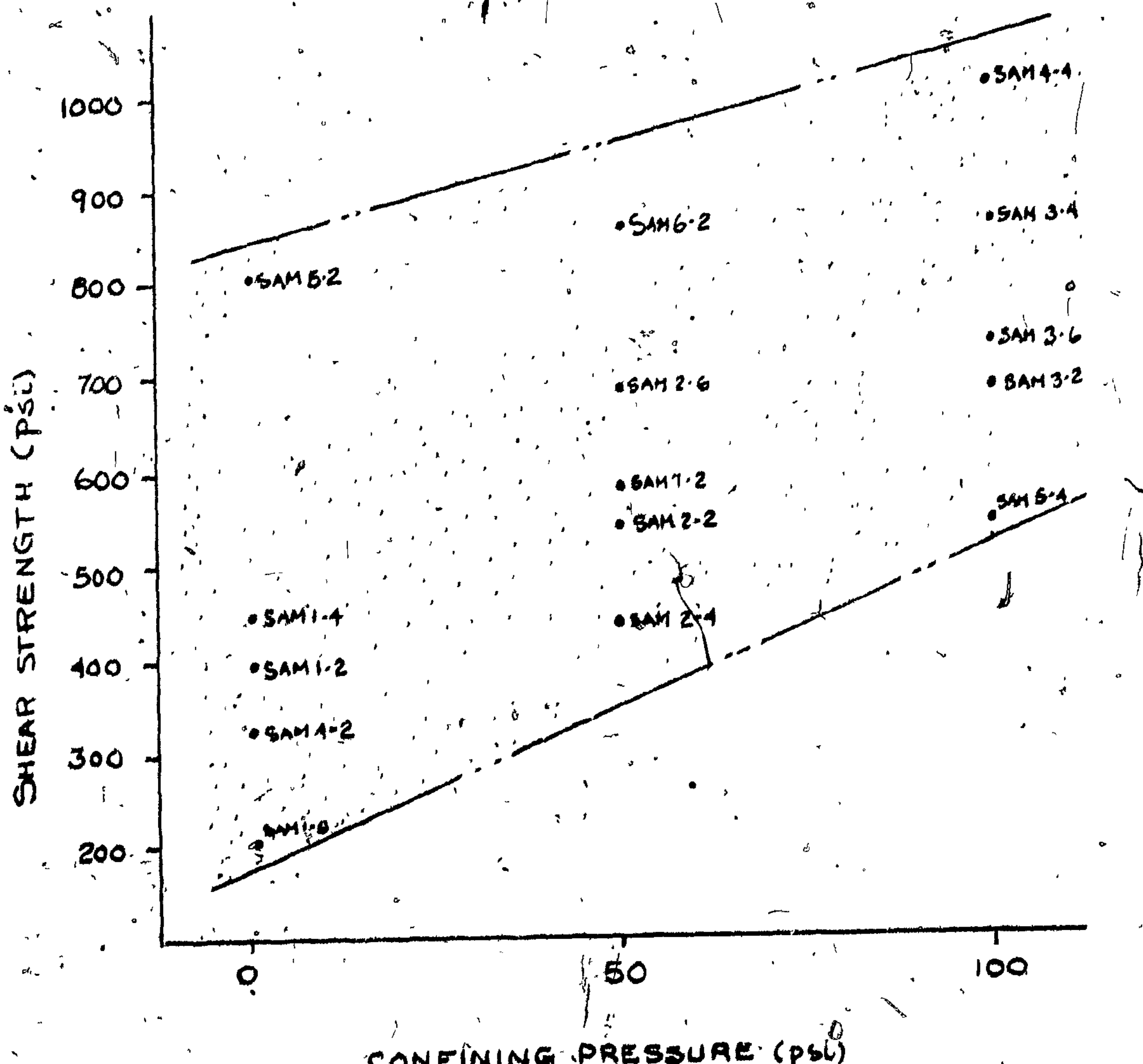


FIGURE 24 - SHEAR STRENGTH versus CONFINING PRESSURE - NATURAL PERMAFROST

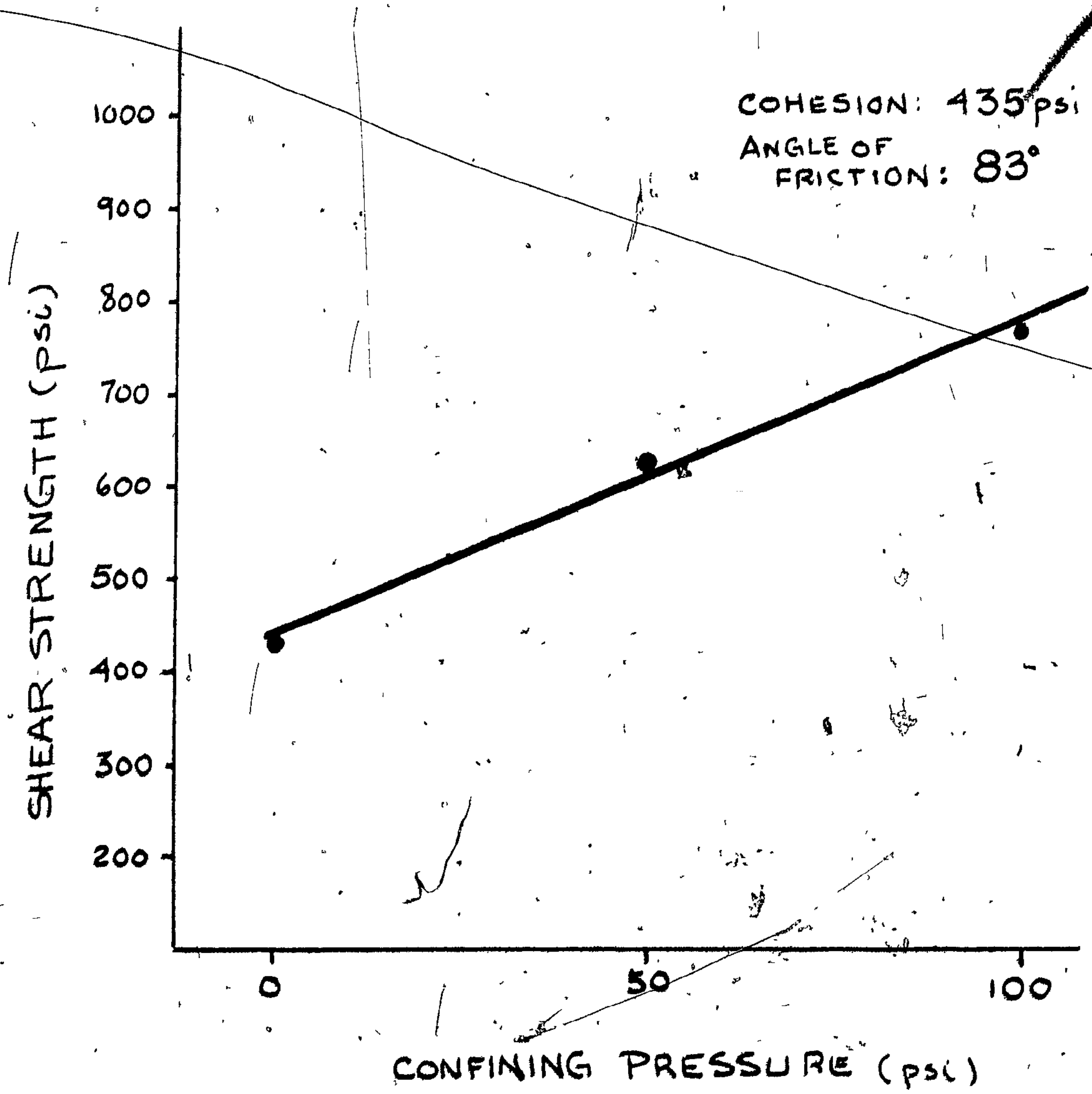


FIGURE 25 - AVERAGE SHEAR STRENGTH VALUES - NATURAL PERMAFROST

with that of unfrozen geological materials, those being typically 20°to 50°. At low confining pressures, it would seem that the ice in the matrix contributes an additional resistance to the frictional resistance of the soil particles themselves. The results of R.N. Yong's work on frozen soils and of ice indicates that the shear strength of ice increases quite rapidly with increases in confining pressures (fig. 26). It is very likely that, until the crushing strength of ice is reached, a high angle of friction will persist. With frozen soils, once the ice matrix has been crushed, residual strength is entirely due to frictional resistance between the soil particles.

This increase in shearing strength with normal stress is further confirmed by C.W. Kaplar's direct shear data, using frozen McNamara concrete sand and blends of Manchester fine sand and East Boston till (20). This data is shown in fig.27. Angles of friction of 70°and 77° were obtained from this data.

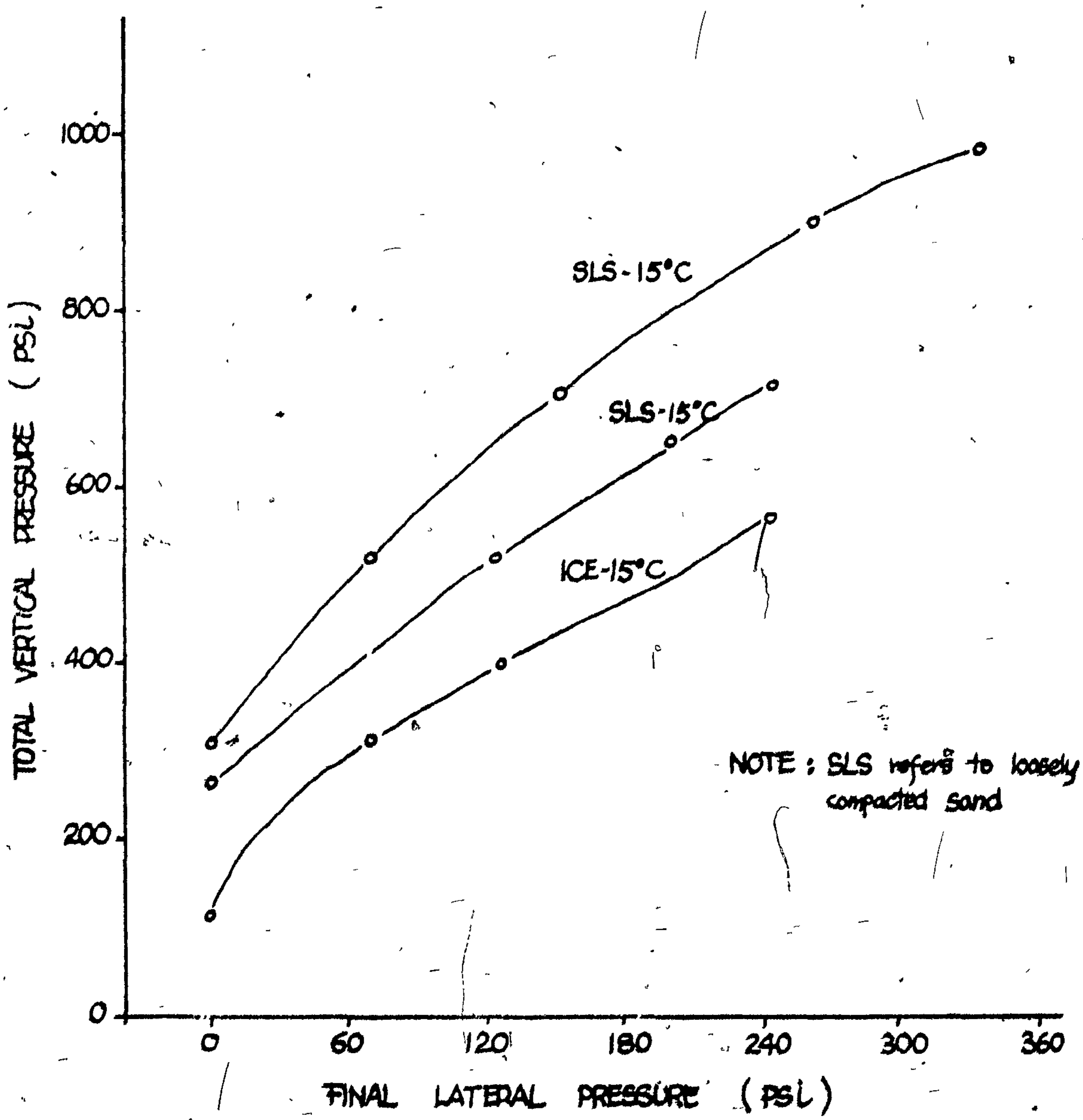


FIGURE 26 – DIRECT SHEAR TESTS
(after YONG (15))

Blend - Manchester Fine Sand & East Boston Till

Point	Normal Load (psi)	Max. Shear Stress (psi)	Water Content %	Degree Ice Sat. %	Unit Dry Density
1	40	840	20.9	100	105
2	70	921	19.3	100	108
3	100	1006	23.2	92	97

McNamara Concrete Sand.

Point	Normal Load psi	Max. Shear Stress-psi	Water Content %	Degree Ice Sat. %	Unit dry weight of [illegible]
1	40	369	15.6	94	114
2	60	405	17.0	100	114
3	80	494	17.7	100	114
4	100	550	16.1	97	114

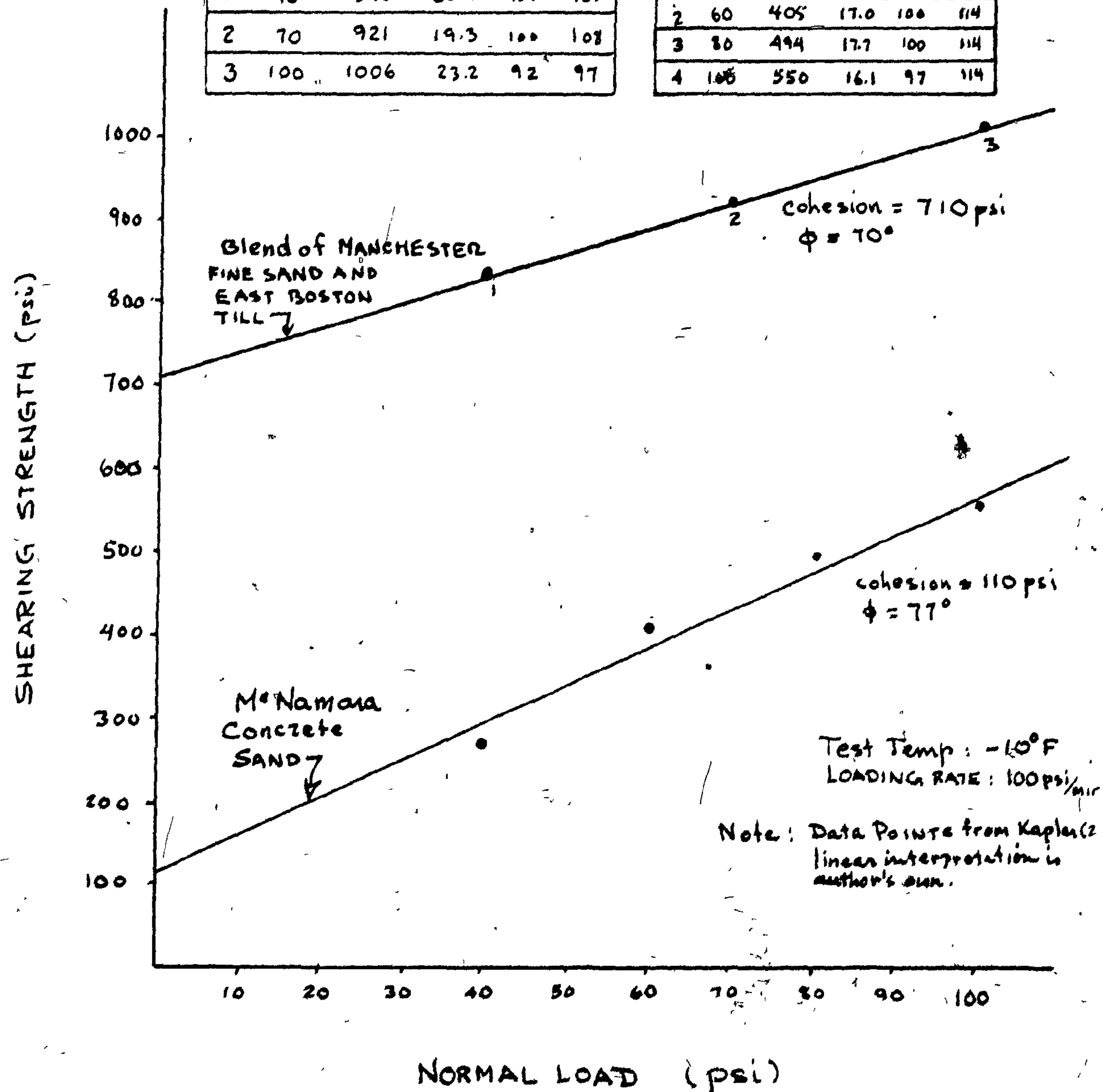


FIGURE 27 - DIRECT SHEAR TESTS
(after KAPLAR (20))

4-4 Remolded Samples:

The natural permafrost samples were remolded and tested to determine the effects of structure on the deformation characteristics and on shear strength. The results are tabulated in Appendix D.

Examining the deformation characteristics of remolded samples, as summarized in figure 28, the curves are noted to be generally similar to those obtained from the natural permafrost samples. However, some differences are apparent. Specifically, deformation characteristics of sets of samples remolded from SAM 2-6 and SAM 3-6 are examined in figure 29. These curves show shallower slopes for the 6" remolded samples than for the natural samples.

As with the natural samples, there appear to be two slopes. The REM 5-4 sample exhibits behavior similar to the REM 4-6 and REM 5-6 samples. However, the remolded 2" samples and the REM 6-4 sample show steeper slopes, at least in their primary deformation stages. It would appear that , at least in the deformation characteristics, the remolded samples do not reflect the same behavior as natural permafrost material, possibly due to differences in density and structure.

The effect of structure on shearing strength is illustrated in figure 30. Except in the case of SAM 2-4, the strength of natural permafrost samples is seen to be greater than that of the same material remolded. In its natural state, SAM 1-6 had a low strength value, probably due to the low moisture

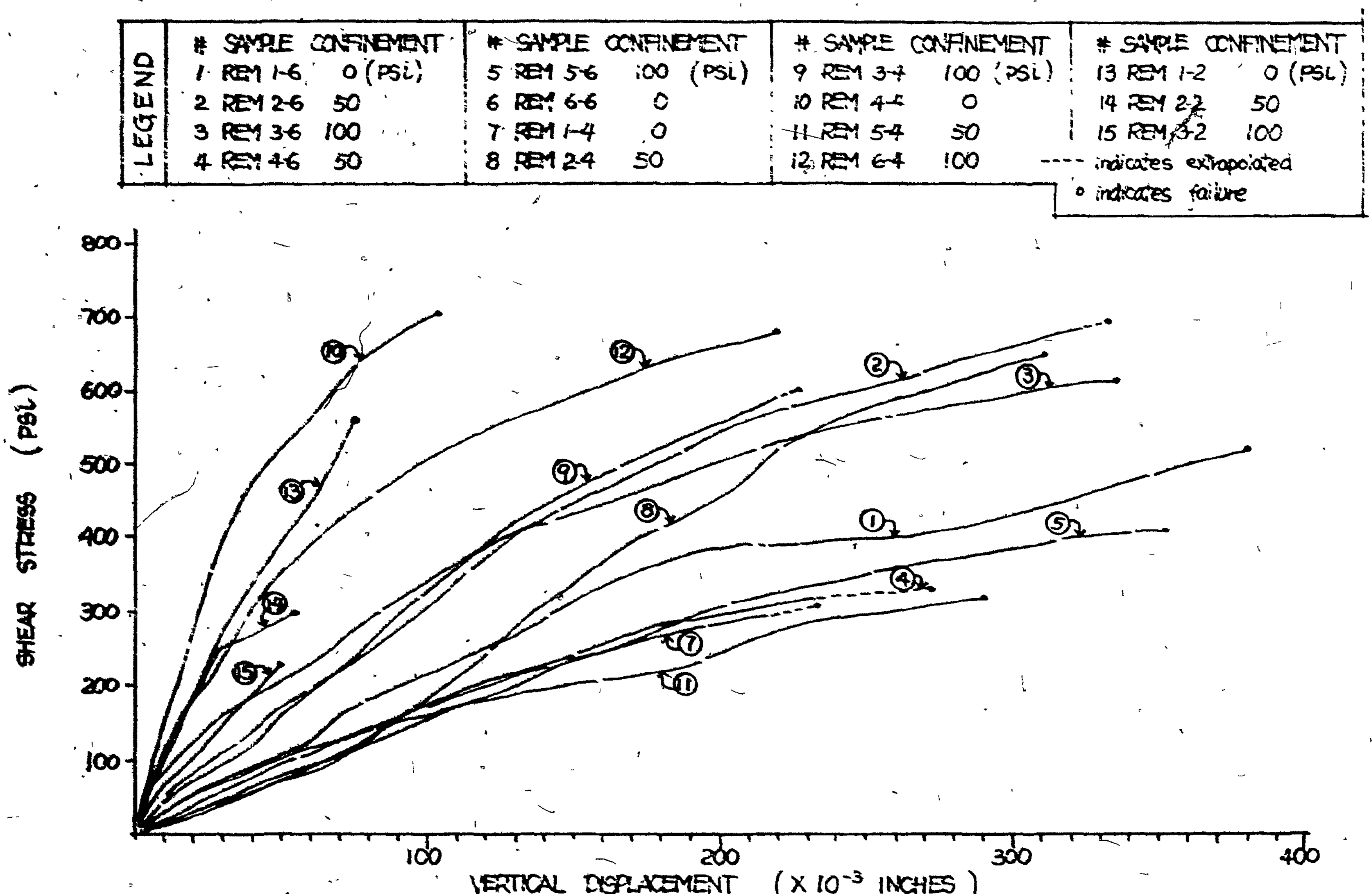


FIGURE 28 - SHEAR STRESS - DISPLACEMENT CURVES - REMOLDED SAMPLES

NOTE : REM 4-6, REM 5-4, REM 2-2 are remolded samples from SAM 2-6 material.
REM 5-6, REM 6-4, REM 3-2 are remolded samples from SAM 3-6 material.

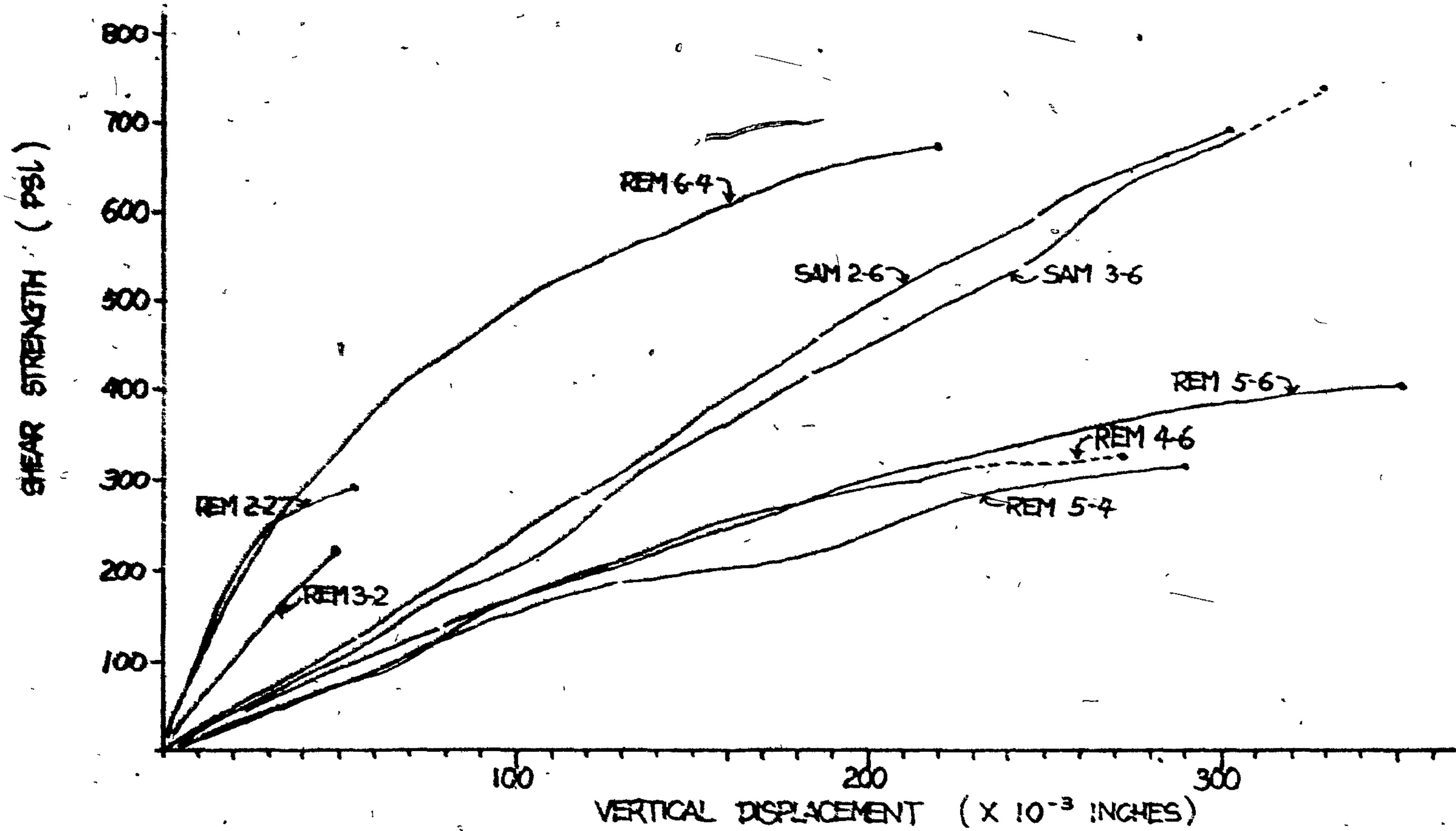


FIGURE 29 - SHEAR STRESS - DISPLACEMENT CURVES
COMPARISON OF NATURAL VERSUS REMOLDED SAMPLES

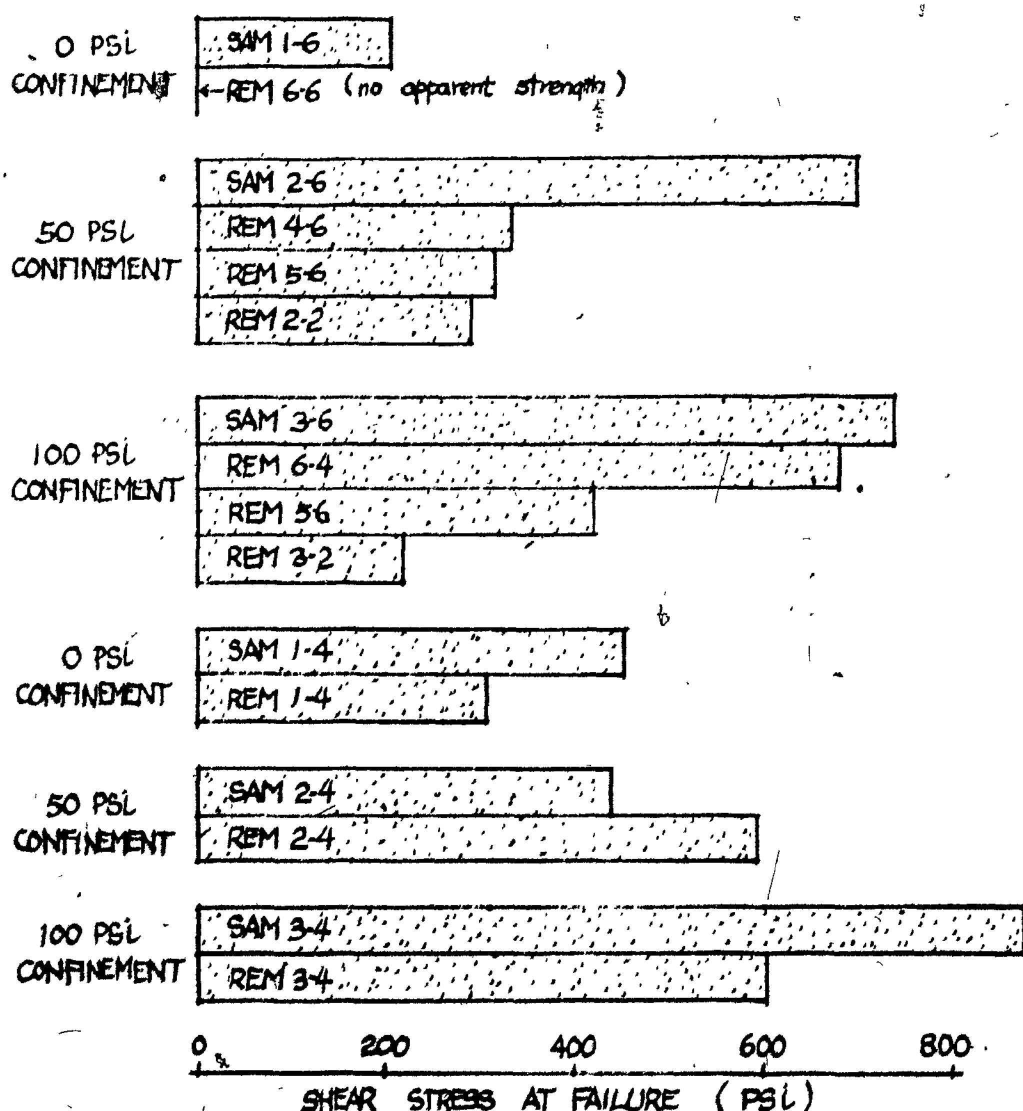


FIGURE 30 - SHEAR STRENGTH
NATURAL VERSUS REMOLDED SAMPLES

content (2.3%). When remolded and tested, no apparent strength value was obtained. Considering natural samples SAM 2-6, 3-6, 1-4, and 3-4, and their remolded counterparts of the same size, we see decreases in shearing strength up to 52%, with average decreases of 40%. SAM 2-4 shows an increase in strength of 32%; however, upon examining figure 28, which shows the erratic behavior of REM 2-4, this increase may be accounted for by irregularities in the shearing plane, possibly large grains. Therefore, the importance of structure on the shearing strength of permafrost is evident. This effect of structure generally represents a decrease in strength of remolded samples. It is also evident that the 6" samples tend to exhibit more consistent and regular results.

4-5 Summary:

From the results discussed, the importance of the effects of structure in assessing the shearing strength of a frozen material can be seen. Although this concept has been generally accepted in theory, experimental data is lacking. It has been shown that, for Middle Iron Formation (MIF), the decrease in shear strength due to remolding is in the order of 40%. As well, the deformation characteristics may also be altered; however, a definite relationship between deformation characteristics and remolding cannot be established from the available data.

Comparisons of the effects of sample size on shear strength show more consistent and linear results where samples of a larger size are used. This justifies the added effort needed in procuring, preparing, and testing such samples.

The shear strength parameters are shown to increase from values of 29° for the angle of friction for unfrozen MIF, to probable values of 83° for the angle of friction with a cohesion of 435 psi for natural permafrost for short-term shear strength at confining pressures to 100 psi.

V - CONCLUSIONS and RECOMMENDATIONS

5-1 General:

The objectives of this study were three-fold:

a) to design a workable shearing apparatus capable of efficiently handling and testing large dimension samples (6" x 6") with the precision required;

b) to establish shear strength parameters for a particular geological material occurring in permafrost, this being MIF;

c) to determine the effects of remolding on the shearing strength of samples of MIF.

As can be seen from the test program, the study was based on a limited number of samples. To claim that the conclusions are beyond question is therefore inaccurate. The areas investigated represent a new and presently poorly understood field of study. It is hoped that more experimental results on natural permafrost material will soon become available, to provide empirical values for use in establishing guidelines when choosing design values for particular engineering problems.

5-2 Conclusions:

From the present study, the following conclusions can be drawn:

1) The shearing apparatus designed, constructed, and used in this project was found to be safe and effective. It functioned satisfactorily in testing shearing strength and deformation characteristics of samples up to 6" x 6" in dimension.

2) The sampling program was successful in procuring and transporting natural permafrost samples.

3) The effect of heat due to friction when cutting and trimming material is more pronounced with smaller dimension samples than with larger ones.

4) For large dimension samples, rough cutting with a band saw and further trimming with a hand-held grinder yielded the best results.

5) The deformation characteristics of large samples are more consistent and linear than the ones obtained for smaller samples.

6) For the material tested, and at low confining pressures (to 100 psi), the shear strength increases with increasing pressure.

In tests on short-term strength, the frozen material yields higher values of cohesion and probably higher values for the angle of friction than the unfrozen material.

7) An average decrease in shearing strength of 40% is seen with testing remolded versus natural samples.

8) The material tested exhibited variability in moisture content, density, and strength, which is typical of all geological materials. The number of samples tested was limited and insufficient to definitively establish the shearing properties of natural permafrost material.

9) A survey of the available literature shows that a definite gap exists in present knowledge of the shearing properties of natural permafrost.

5-3 Recommendations:

1) More extensive testing of natural permafrost should be done to establish the distribution of strengths and shearing characteristics.

2) Large (at least 6" x 6") samples should be used when determining shear strength parameters.

3) The effects of the gap dimension between the shear box halves on the shearing characteristics of materials should be investigated.

4) To avoid the problems and expense associated with transporting natural permafrost material, testing should be conducted as closely as possible to the sampling site.

5) Further research into sample preparation techniques and their effects on sample integrity would be valuable.

6) The effects of loading rate, moisture content (in both frozen and unfrozen material), density, and temperature on the shearing strength of natural permafrost must be quantified.

7) The relationships between short-term and long-term shear strength should be determined, enabling the determination of long-term shear strength by using the more time-efficient short-term shear strength test.

BIBLIOGRAPHY

1) The Mining Association of Canada, 1974 - "Mining / What Mining Means to Canada", p. 35-37.

2) Judge, A.S., 1973 - "The Prediction of Permafrost Thickness" Canadian Geotechnical Journal, Feb.

3) Muller, S.W., 1947 - "Permafrost or Permanently Frozen Ground and Related Engineering Problems", J.W. Edwards, Inc.

4) Brown, J.E. and T.L. Pewe, 1973 - "Distribution of Permafrost in North America and Its Relationship to the Environment: A Review, 1963-1973", p. 71-100.

5) Lambe, T.W., 1951 - "Soil Testing for Engineers", J. Wiley and Sons, Inc.

6) American Society for Testing Materials, 1970 - "Special Procedures for Testing Soil and Rock for Engineering Purposes", STP # 479, 5th Edition.

7) Terzaghi, k. and R.B. Peck, 1967 - "Soil Mechanics in Engineering Practice", J. Wiley and Sons, Inc.

8) Tsytovich, N.A. and M.I. Sumgin, 1937 - "The Principles of Mechanics of Frozen Ground", SIPRE Trans. 19.

9) Vyalov, S.S., 1965 - "The Strength and Creep of Frozen Soils and Calculations for Ice-Soil Retaining Strucures", U.S. Army CRREL, Trans. 76.

10) Vyalov, S.S., 1959 - "Rheological Properties and Bearing Capacity of Frozen Soils", U.S. Army CRREL, Trans. 74.

11) Gray, J.T., 1964 - "Permafrost Studies at Knob Lake, Central Labrador, Ungava", McGill Sub-Arctic Research Paper No. 21, p. 129-134

12) Nicholson, F.H. and H.B. Granberg, 1973 - "Permafrost and Snow Cover Relationships Near Schefferville", Proceedings, North American Contribution, Second International Conference on Permafrost, National Academy of Sciences, Wahington, D.C.

13) Nicholson, F.H. and B.G. Thom, 1973 - "Studies at the Timmins 4 Permafrost Experimental Site", Proceedings, North American Contribution, Second International Conference on Permafrost, National Academy of Sciences, Washington, D.C.

14) Yap, S.K., 1972 - "Engineering Properties of Frozen Ores from Labrador", M. Eng. Thesis, McGill University.

15) Yong, R.N., 1959 - "Some Shearing Characteristics of Frozen Soil", Report No. D.Phys. R(G) Misc.S.2, Defence Research Board, Department of National Defence, Ottawa.

16) Anderson, D.M. and N.R. Morgenstern, 1973 - "Physics, Chemistry, and Mechanics of Frozen Ground: A Review", p. 257-288, Proceedings, North American Contribution, Second International Conference on Permafrost, National Academy of Sciences, Washington D.C.

17) Vyalov, S.S. and S.T. Tsytovich, 1955 - "Cohesion of Frozen Soils", Dokl. Akad. Nauk. 4(104):527-529

18) Sayles, F.H., 1973 - "Triaxial and Creep Tests on Frozen Ottawa Sand", p. 384-391, Proceedings, North American Contribution, Second International Conference on Permafrost, National Academy of Sciences, Washington D.C.

19) Gold, L.W. and A.H. Lachenbruch, 1973 - "Thermal Conditions in Permafrost - Areview of North American Literature", p. 3-23, Proceedings, North American Contribution, Second International Conference on Permafrost, National Academy of Sciences, Washington D.C.

20) Kaplar, C.W., 1971 - "Some Strength Properties of Frozen Soil and Effects of Loading Rate", U.S. Army CRREL Spec. Rept. 159.

21) Vyalov, S.S., 1966 - "Rheology of Frozen Soils", p.332-337, Permafrost: Proceedings of an International Conference, National Academy of Sciences, Washington D.C.

22) Sayles, F.H., 1968 - "Creep of Frozen Sands", CRREL Technical Report 190, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire,

23) McRoberts, E.C. and N.R. Morgenstern, 1974 - "Stability of Slopes in Frozen Soil, Mackenzie Valley, N.W.T.", p. 554-574, Canadian Geotechnical Journal, Vol. II, #4.

24) Bowers, J.F., 1963 - "Strength Testing of Soils", p. 3-22, Laboratory Shear Testing of Soils, ASTM Special Publication No. 361, Philadelphia, Pa.

25) Lajtai, E.Z., 1969 - "Shear Strength of Weakness Planes in Rock", International Journal of Rock Mechanics and Mining Sciences, Sept.

26) Stubbins, J.B., R.A. Blais, and I.S. Zajac, 1961 - "Origin of the Soft Iron Ores of the Knob Lake Range", p. 1-16, Can. Mining and Metall. Bull. 64.

27) Thom, B.G., 1969 - "New Permafrost Investigations near Schefferville, P.Q.", p. 317-327. Rev. Geogr. Montreal.

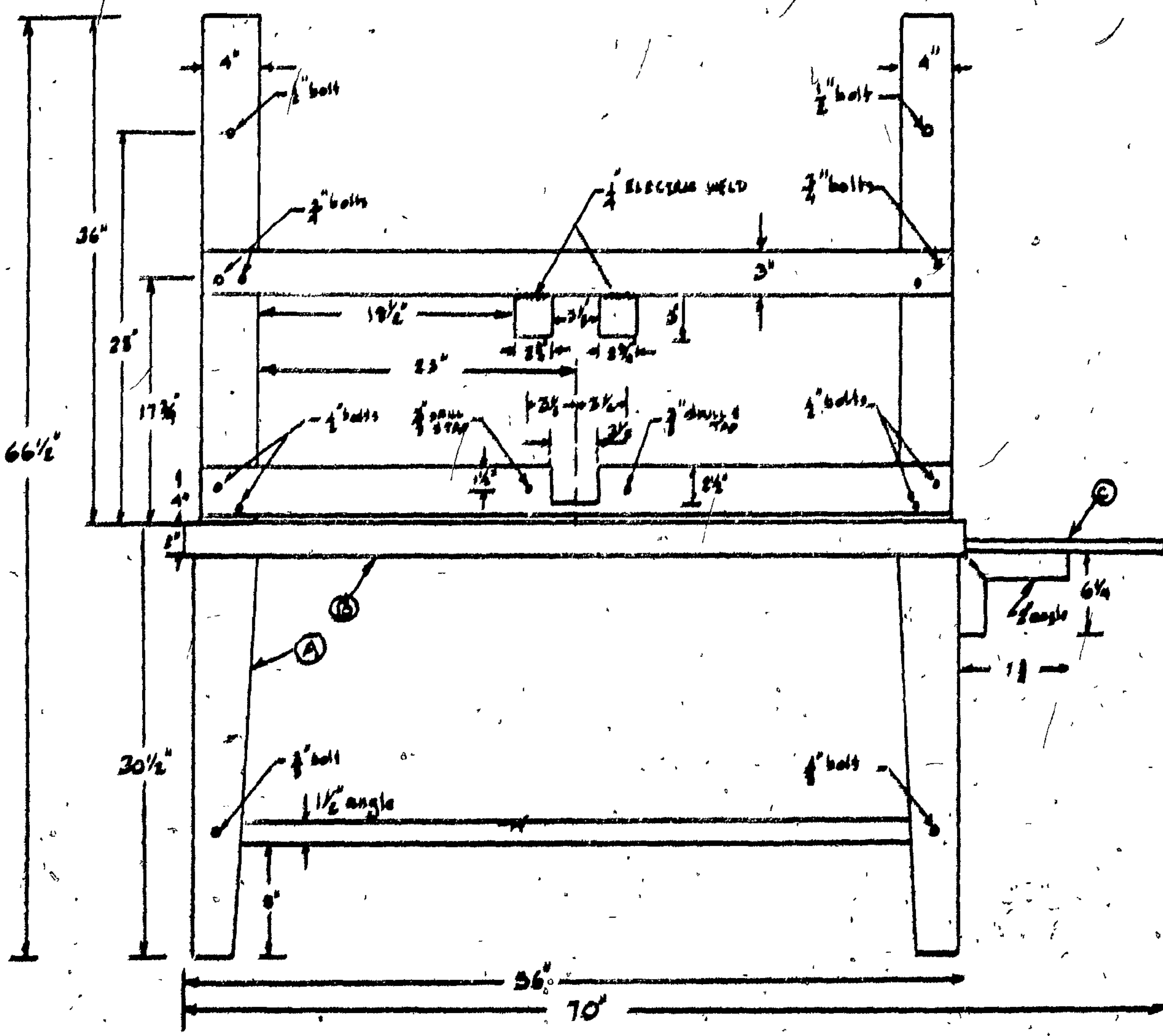
28) Bird, J.B.(ed.), 1964 - "Permafrsot Studies in Central Labrador - Ungava", McGill Sub-Arctic Research Papers 16.

29) Annerstern, L.J., 1966 - "Interaction Between Surface Cover and Permafrost", Biul. Peryglacj. 15:27-33.

30) Garg, O. and B.G. Thom, 1950 - "Report of Permafrost Investigations at Timmins 1 - Summer 1970", Tech. Services Project No. 6908, Report 1, Iron Ore Company of Canada, Schefferville.

APPENDIX A

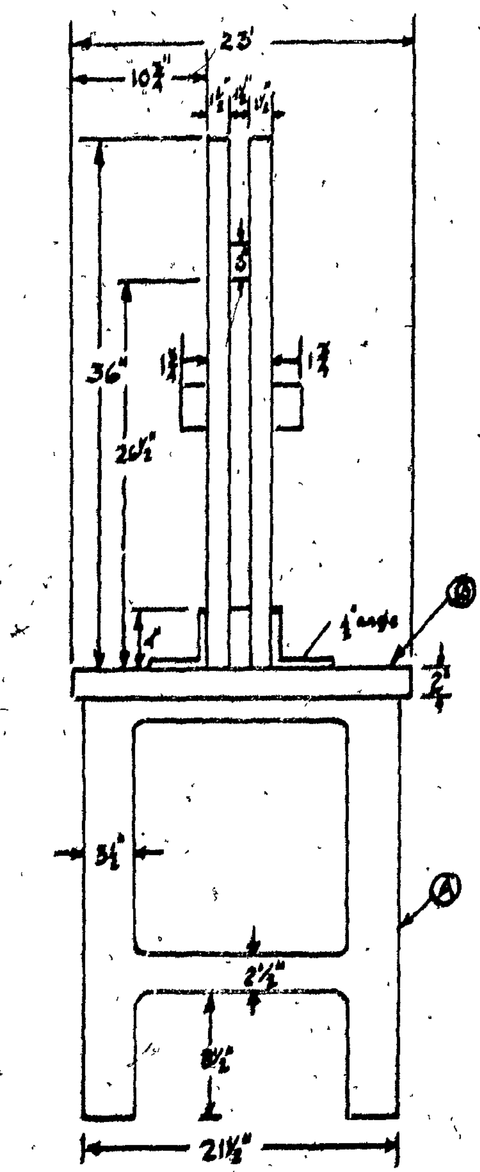
MECHANICAL DRAWINGS for 100T DOUBLE DIRECT SHEARING MACHINE



MATERIALS: A - CAST IRON
B - CAST IRON
C - PLYWOOD
ALL OTHER - STEEL

Scale: 0 1 2 3 4 inches

FIGURE A-1 DRAWING OF FRAME-FRONT VIEW



MATERIALS: A - CAST IRON B - CAST IRON C - PLYWOOD ALL OTHER - STEEL	Scale 0 1 2 3 4 inches

FIGURE A-2 DRAWING OF FRAME - SIDE VIEW

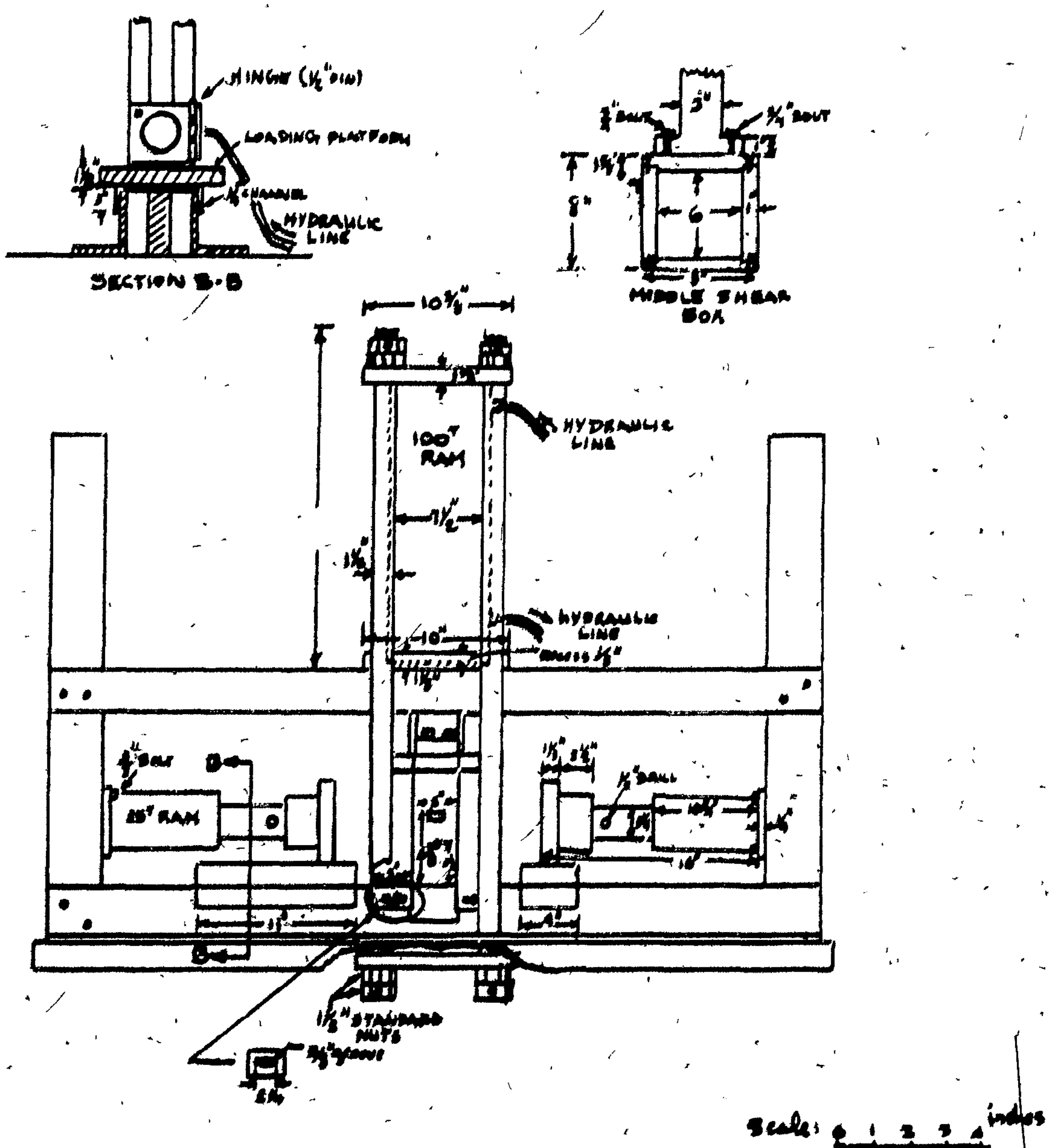


FIGURE A-3 DRAWING OF SHEARING APPARATUS

APPENDIX B

CALIBRATION CURVES for VERTICAL and HORIZONTAL LOADING RAMS

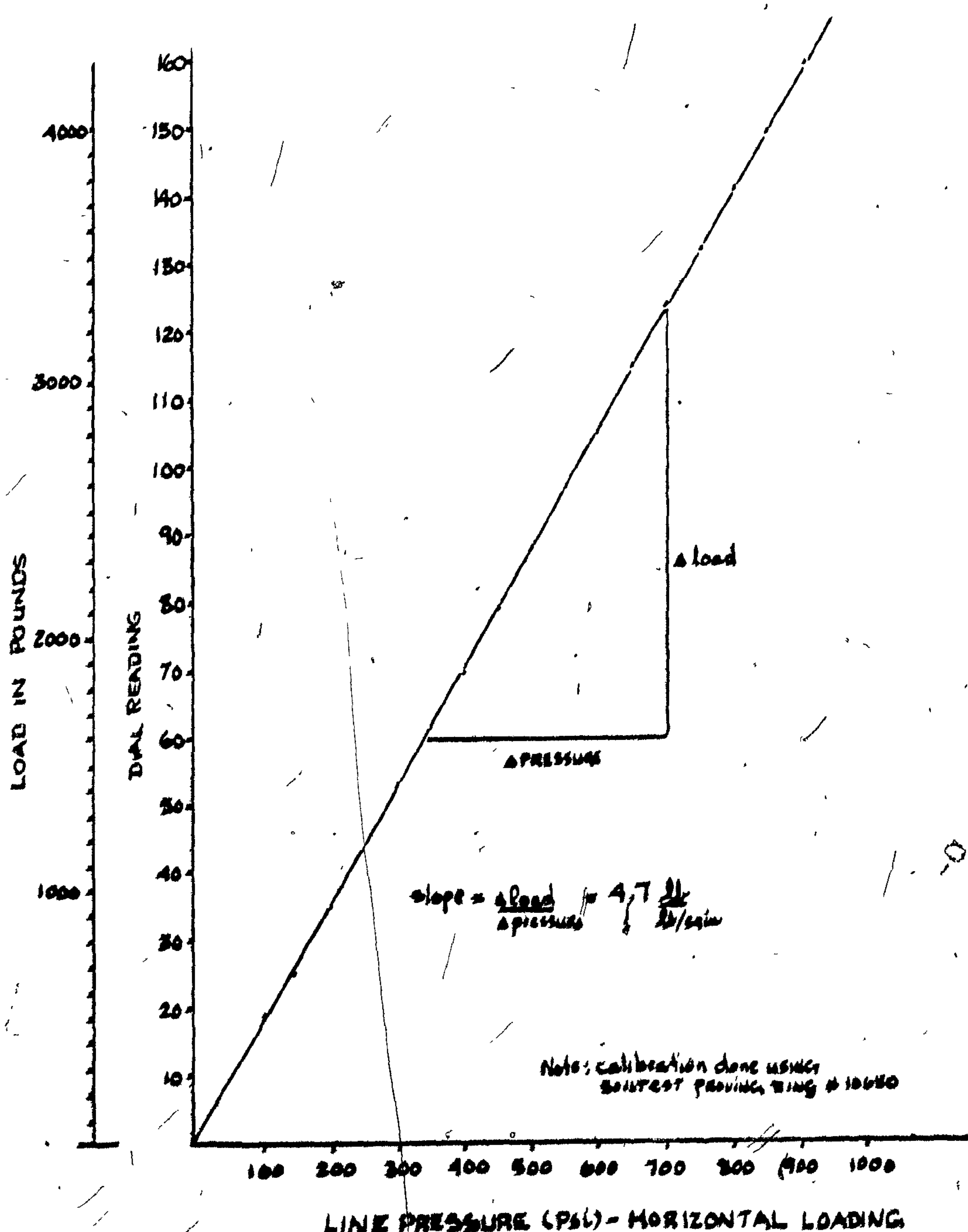


FIGURE B-1 CALIBRATION CURVE for HORIZONTAL PRESSURE GAUGE

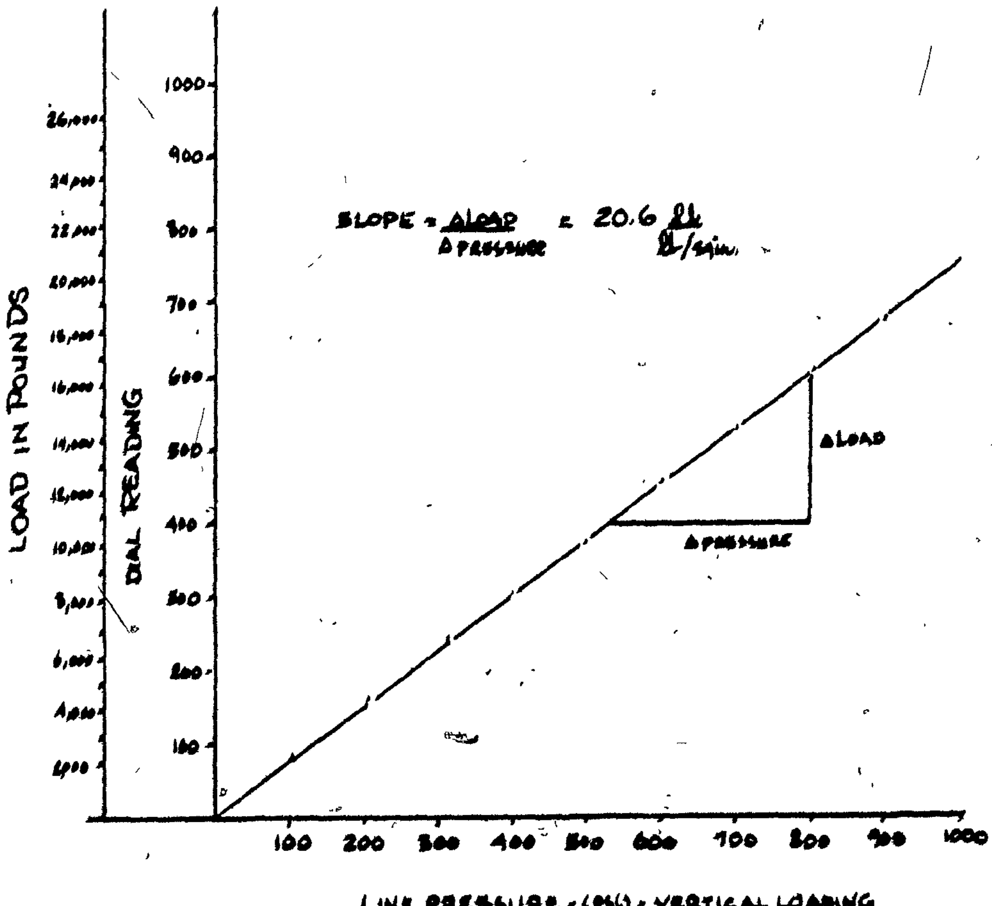


FIGURE B-2 CALIBRATION CURVE for VERTICAL PRESSURE GAUGE

APPENDIX C

PROCEDURES for DENSITY DETERMINATION of FROZEN SOILS

PROCEDURES FOR DENSITY DETERMINATION OF FROZEN SOILS

Introduction: The following is an outline of a procedure for determining the bulk density of a sample of frozen soil. The method is efficient and sufficiently precise for a quick determination of density under environmental conditions.

Materials:

Graduated cylinder - 1 liter capacity with 15 ml. graduations.

Graduated cylinder - 250 ml. capacity with 1 ml. graduations.

Uniform sand (Ottawa Sand or equivalent).

Beam balance - reading to 0.1 gm.

Procedure:

- Chip down sample to obtain a roughly regular piece, smaller than the inside diameter of the 1 L. grad. cylinder.
- Weigh the sample to within o.1 gm and record.
- Pour 100 ml of sand into the bottom of the 1 L grad. cylinder.
- Slide in sample.
- With the 100 ml grad. cylinder, pour in measured amounts of sand to completely submerge the sample, filling the 1 L grad. cylinder to the closest 100 ml mark. Be sure the sand is level when reading.

- Record the volume of sand needed to submerge the sample.

Sample Calculations:

weight of sand =	210.5	gm	(1)
Volume of sand + sample =	300	ml	(2)
Volume of sand used =	230	ml	(3)
Volume of sample =	70	ml	(2-3)

$$\text{Density} = \frac{\text{wt. of sample}}{\text{vol. of sample}} = \frac{210.5}{70} = 3.0 \text{ gm/cc}$$

Notes:

- Avoid tapping the grad. cylinder, as this will induce compaction and lead to erroneous results.
- Repeat the test until two consecutive, consistent results are obtained.

APPENDIX D

TABLES - LAB DATA and RESULTS

TABLE D-1 LAB DATA AND RESULTS

SAMPLE: SAM 1-6

DIMENSIONS: 5.62" x 5.77" x 6.875"

SHEARING AREA: 64.88 in^2

HORIZONTAL CONFINING PRESSURE: 0 psi

TEST TEMPERATURE: 25^{0}F

DENSITY : 3.0gm/cc.

MOISTURE CONTENT: 2.3%

LOADING RATE: 100 psi/min

LINE PRESSURE psi	SHEAR LOAD lb	SHEAR STRESS psi	VERTICAL DISPLACEMENT $x10^{-3}$in	REMARKS
0	0	0	0	Natural permafrost
100	2,060	31.7	9	sample.
200	4,120	63.5	22	
300	6,180	95.3	40	Stress at failure: 206 psi
400	8,240	127.0	55	
500	10,300	158.7	80	* - no reading taken
600	12,360	190.5	89	
650	13,390	206.4	*	

TABLE D-2 LAB DATA AND RESULTS

SAMPLE: SAM 2-6

DIMENSIONS: 5.70" x 5.85" x 6.75"

SHEARING AREA: 66.69 in.^{2}

HORIZONTAL CONFINING PRESSURE: 50 psi

TEST TEMPERATURE: 25°F

DENSITY: 3.15 gm/cc.

MOISTURE CONTENT: 7.3%

LOADING RATE: 173 psi/min

LINE PRESSURE psi	SHEAR LOAD lb	SHEAR STRESS psi	VERTICAL DISPLACEMENT $x10^{-3}$ in	REMARKS
0	0	0	0	
250	5,150	77.2	33	Natural permafrost sample.
500	10,300	154.4	65	
750	15,450	231.7	96	
1,000	20,600	308.9	126	Stress @ failure: 695 psi
1,250	25,750	386.1	154	
1,500	30,900	463.3	185	
1,750	36,050	540.6	222	
2,000	41,200	617.8	256	
2,250	46,350	695.0	300	

TABLE D-3 LAB DATA AND RESULTS

SAMPLE: <u>SAM 3-6</u>

DIMENSIONS: 5.83" x 5.75" x 8.75"

SHEARING AREA: 67.04 in^2

HORIZONTAL CONFINING PRESSURE: 100 psi

TEST TEMPERATURE: 25°F

DENSITY: 3.3 gm/cc.

MOISTURE CONTENT: 10.2%

LOADING RATE: *

LINE PRESSURE psi	SHEAR LOAD lb	SHEAR STRESS psi	VERTICAL DISPLACEMENT $x10^{-3}$in	REMARKS
0	0	0	0	
250	5,150	76.8	45	Natural permafrost
500	10,300	153.6	77	sample.
750	15,450	230.5	115	
1,000	20,600	307.3	131	Stress @ failure: 738 psi
1,250	25,750	384.1	167	
1,500	30,900	460.9	203	* - no reading taken
1,750	36,070	538.0	245	
2,000	41,200	614.5	265	
2,250	46,350	691.4	395	SAM 2-2, 3-2, 4-2, & 3-6
2,400	49,440	737.5	*	were cut from same block.

TABLE D-4 LAB DATA AND RESULTS

SAMPLE: SAM 1-4

DIMENSIONS: 3.81" x 3.90" x 6"

SHEARING AREA: 29.72 in^2

HORIZONTAL CONFINING PRESSURE: 0 psi

TEST TEMPERATURE: 25°F

DENSITY: 3.3 gm/cc

MOISTURE CONTENT: 4.9%

LOADING RATE: 225 psi/min

LINE PRESSURE psi	SHEAR LOAD lb	SHEAR STRESS psi	VERTICAL DISPLACEMENT $x10^{-3}$ in	REMARKS
0	0	0	0	
50	1,030	34.7	7	Natural permafrost
100	2,060	69.3	15	sample.
150	3,090	103.9	33	
200	4,120	138.6	44	Stress @ failure: 450 psi
250	5,150	173.3	49	
300	6,180	208.0	59	
350	7,210	242.6	73	
400	8,240	277.3	87	
450	9,270	311.9	99	
500	10,300	346.6	109	
550	11,330	381.2	118	
600	12,360	415.9	129	
650	13,390	450.5	144	

TABLE D-5 LAB DATA AND RESULTS

SAMPLE: SAM 2-4

TEST TEMPERATURE: 25°F

DIMENSIONS: 3.945" x 3.86" x 5.5"

DENSITY: 3.2 gm/cc.

SHEARING AREA: 30.45 in^2

MOISTURE CONTENT: 10.0%

HORIZONTAL CONFINING PRESSURE: 50 psi

LOADING RATE: 109 psi/min

LINE PRESSURE psi	SHEAR LOAD lb	SHEAR STRESS psi	VERTICAL DISPLACEMENT $x10^{-3}$in	REMARKS
0	0	0	0	
50	1,030	33.8	13	Natural permafrost
100	2,060	67.6	29	sample.
150	3,090	101.5	48	
200	4,120	135.3	63	Stress @ failure: 440 psi
250	5,150	169.1	87	
300	6,180	202.9	103	
350	7,210	236.8	119	
400	8,240	270.6	141	
450	9,270	304.4	163	
500	10,300	338.3	183	
550	11,330	372.1	203	
600	12,360	405.9	220	
650	13,390	439.7	234	

TABLE D-6 LAB DATA AND RESULTS

SAMPLE: SAM 3-4
DIMENSIONS: 4.00" x 3.71" x 6"
SHEARING AREA: 29.68 in^2
HORIZONTAL CONFINING PRESSURE: 100 psi

TEST TEMPERATURE: 25°F
DENSITY: 3.3 g/cc.
MOISTURE CONTENT: 10.3%
LOADING RATE: 216 psi/min

LINE PRESSURE psi	SHEAR LOAD lb	SHEAR STRESS psi	VERTICAL DISPLACEMENT $x10^{-3}$ in	REMARKS
0	0	0	0	
50	1,030	34.7	4	Natural permafrost
100	2,060	69.4	15	sample.
150	3,090	104.1	28	
200	4,120	138.8	39	Stress @ failure: 868 psi
250	5,150	173.5	54	
300	6,180	208.2	64	* - no reading taken
350	7,210	242.9	75	
400	8,240	277.6	92	
450	9,270	312.3	104	
500	10,300	347.0	114	
550	11,330	381.7	124	
600	12,360	416.4	136	
650	13,390	451.1	149	
700	14,420	485.8	159	
750	15,450	520.5	169	
800	16,480	555.3	182	
850	17,510	589.9	194	
900	18,5[illegible]0	6[illegible]4.7	[illegible]	

TABLE D-7 LAB DATA AND RESULTS

SAMPLE: SAM 4-4 — TEST TEMPERATURE: 25°F

DIMENSIONS: 3.875" x 3.94" x 7.5" — DENSITY: 3.2 gm/cc.

SHEARING AREA: 30.54 in² — MOISTURE CONTENT: 10.3%

HORIZONTAL CONFINING PRESSURE: 100 psi — LOADING RATE: *

LINE PRESSURE psi	SHEAR LOAD lb	SHEAR STRESS psi	VERTICAL DISPLACEMENT $x10^{-3}$ in	REMARKS
0	0	0	0	
100	2,060	67.4	10	Natural permafrost
200	4,120	134.9	30	sample.
300	6,180	202.3	60	
400	8,240	269.8	83	Stress @ failure:1012 psi
500	10,300	337.3	105	
600	12,360	404.7	116	SAM 4-4 and 5-4 were cut
700	14,420	472.2	122	from the same block.
800	16,480	539.6	132	
900	18,540	607.1	145	* - no reading taken
1,000	20,600	674.5	170	
1.100	22,660	741.9	188	
1,500	30,900	1011.7	*	

TABLE D-8 LAB DATA AND RESULTS

SAMPLE: SAM 5-4

TEST TEMPERATURE: 25°F

DIMENSIONS: 3.925" x 3.87" x 7.375"

DENSITY: 3.3 gm/cc.

SHEARING AREA: 30.38 in²

MOISTURE CONTENT: 4.1%

HORIZONTAL CONFINING PRESSURE: 50 psi

LOADING RATE: *

LINE PRESSURE psi	SHEAR LOAD lb	SHEAR STRESS psi	VERTICAL DISPLACEMENT $x10^{-3}$in	REMARKS
0	0	0	0	
50	1.030	33.9	10	Natural permafrost
100	2,060	67.8	19	sample.
150	3,090	101.7	32	
200	4,120	135.6	63	Stress @ failure: 543 psi
250	5,150	169.5	88	
300	6,180	203.4	120	SAM 5-3 and 5-4 were cut
350	7,210	237.3	145	from the same block.
400	8,240	271.2	160	
450	9,270	305.1	170	* - no reading taken
800	16,480	542.5	*	

TABLE D-9 LAB DATA AND RESULTS

SAMPLE: SAM 1-2

DIMENSIONS: 1.985" x 1.985" x 4.275"

SHEARING AREA: 7.88 in^2

HORIZONTAL CONFINING PRESSURE: 0 psi

TEST TEMPERATURE: 25^{0}F

DENSITY: 2.5 gm/cc.

MOISTURE CONTENT: 10.3%

LOADING RATE: 400 psi/min

LINE PRESSURE psi	SHEAR LOAD lb	SHEAR STRESS psi	VERTICAL DISPLACEMENT $x10^{-3}$in	REMARKS
0	0	0	0	
50	1,030	130.7	10	Natural permafrost sample.
100	2,060	261.4	30	
150	3,090	392.1	40	Stress @ failure: 393 psi

TABLE D-10 LAB DATA AND RESULTS

SAMPLE: SAM 2-2

DIMENSIONS: 1.945" x 1.945" x 6.25"

SHEARING AREA: 7.56 in^2

HOIZONTAL CONFINING PRESSURE: 50 psi

TEST TEMPERATURE: 25°F

DENSITY: 3.0 gm/cc.

MOISTURE CONTENT: 11.9%

LOADING RATE: 500 psi/min

LINE PRESSURE psi	SHEAR LOAD lb	SHEAR STRESS psi	VERTICAL DISPLACEMENT $x10^{-3}$in	REMARKS
0	0	0	0	
50	1,030	136.2	8	Natural permafrost sample.
100	2,060	272.5	23	
150	3,090	408.7	54	Stress @ failure: 545 psi
200	4,120	544.9	138	SAM 2-2, 3-2, 4-2 & 3-6 were cut from same block.

TABLE D-11 LAB DATA AND RESULTS

SAMPLE: SAM 3-2

DIMENSIONS: 1.93" x 1.95" x 5.6"

SHEARING AREA: 7.53 in^2

HORIZONTAL CONFINING PRESSURE: 100 psi

TEST TEMPERATURE: 25^0F

DENSITY: 3.1 gm/cc.

MOISTURE CONTENT: 11.6%

LOADING RATE: 684 psi/min

LINE PRESSURE psi	SHEAR LOAD lb	SHEAR STRESS psi	VERTICAL DISPLACEMENT $x10^{-3}$in	REMARKS
0	0	0	0	
50	1,030	136.7	17	Natural permafrost sample.
100	2,060	273.6	35	
150	3,090	410.4	53	Stress @ failure: 684 psi
200	4,120	547.1	72	
250	5,150	683.9	167	SAM 2-2, 3-2, 4-2 & 3-[illegible] were cut from same block.

TABLE D-12 LAB DATA AND RESULTS

SAMPLE: SAM 4-2

DIMENSIONS: 1.60" x 1.98" x 6.25"

SHEARING AREA: 6.34 in^2

HORIZONTAL CONFINING PRESSURE: 0 psi

TEST TEMPERATURE: 25°F

DENSITY: 3.1 gm/cc.

MOISTURE CONTENT: 11.2%

LOADING RATE: *

LINE PRESSURE psi	SHEAR LOAD lb	SHEAR STRESS psi	VERTICAL DISPLACEMENT $x10^{-3}$in	REMARKS
100	2,060	325	*	Natural permafrost sample. Approximate stress @ failure: 325 psi * - no reading taken SAM 2-2, 3-2, 4-2 & 3-6 were cut from same block.

TABLE D-13 LAB DATA AND RESULTS

SAMPLE: SAM 5-2

DIMENSIONS: 1.935" x 1.975" x 7.25"

SHEARING AREA: 7.64 in^2

HORIZONTAL CONFINING PRESSURE: 9 psi

TEST TEMPERATURE: 25°F

DENSITY: 3.3 gm/cc.

MOISTURE CONTENT: 9.2%

LOADING RATE: 539 psi/min

LINE PRESSURE psi	SHEAR LOAD lb	SHEAR STRESS psi	VERTICAL DISPLACEMENT $x10^{-3}$ in	REMARKS
0	0	0	0	
50	1,030	134.8	11	Natural permafrost sample.
100	2,060	269.6	26	
150	3,090	404.4	39	Stress @ failure: 809 psi
200	4,120	539.3	56	
250	5,150	674.1	85	* - no reading taken
300	6,180	808.9	*	SAM 5-2, 6-2 & 7-2 were cut from the same block.

TABLE D-14 LAB DATA AND RESULTS

SAMPLE: SAM 6-2

DIMENSIONS: 1.975" x 1.97" x 7.625"

SHEARING AREA: 7.78 in^2

HORIZONTAL CONFINING PRESSURE: 50 psi

TEST TEMPERATURE: 25^0F

DENSITY: 3.2 gm/cc.

MOISTURE CONTENT: 6.2%

LOADING RATE: 860 psi/min

LINE PRESSURE psi	SHEAR LOAD lb	SHEAR STRESS psi	VERTICAL DISPLACEMENT $x10^{-3}$in	REMARKS
0	0	0	0	
50	1,030	132.4	20	Natural permafrost sample.
100	2,060	264.8	60	
150	3,090	397.2	75	Stress @ failure: 860 psi
200	4,120	529.6	90	
250	5,150	661.9	116	SAM 5-2, 6-2 & 7-2 were cut from the same block.
300	6,180	794.3	137	
325	6,700	860.5	*	

* - no reading taken

TABLE D-15 DATA AND RESULTS

SAMPLE: SAM 7-2

DIMENSIONS: 1.80" x 1.96" x 7.375"

SHEARING AREA: 7.06 in^2

HORIZONTAL CONFINING PRESSURE: 50 psi

TEST TEMPERATURE: 25^0F

DENSITY: 3.1 gm/cc.

MOISTURE CONTENT: 11.7%

LOADING RATE: *

LINE PRESSURE psi	SHEAR LOAD lb	SHEAR STRESS psi	VERTICAL DISPLACEMENT $x10^{-3}$in	REMARKS
0	0	0	0	
50	1,030	145.9	10	Natural permafrost sample.
100	2,060	291.8	45	
150	3,090	437.7	90	Stress @ failure: 584 psi
200	4,120	583.6	150	SAM 5-2, 6-2 & 7-2 were cut from the same block.
				* - no reading taken

TABLE D-16 LAB DATA AND RESULTS

SAMPLE: SAM 8-2

DIMENSIONS: 1.975" x 1.925" x 7"

SHEARING AREA: 7.60 in^2

HORIZONTAL CONFINING PRESSURE: 100 psi

TEST TEMPERATURE: 25°F

DENSITY: 3.0 gm/cc.

MOISTURE CONTENT: 5.2%

LOADING RATE: *

LINE PRESSURE psi	SHEAR LOAD lb	SHEAR STRESS psi	VERTICAL DISPLACEMENT $x10^{-3}$ in	REMARKS
0	0	0	0	
50	1,030	135.5	17	Natural permafrost sample.
100	2,060	271.1	32	
150	3,090	406.6	57	Stress @ Failure: 407 psi

* - no reading taken

TABLE D-17 LAB DATA AND RESULTS

SAMPLE: REM 1-6
DIMENSIONS: 5.94" x 5.99" x 7.875"
SHEARING AREA: 71.18 in^2
HORIZONTAL CONFINING PRESSURE: 0 psi

TEST TEMPERATURE: 25°F
DENSITY: 3.3 gm/cc.
MOISTURE CONTENT: 8.5%
LOADING RATE: 104 psi/min

LINE PRESSURE psi	SHEAR LOAD lb	SHEAR STRESS psi	VERTICAL DISPLACEMENT $x10^{-3}$ in	REMARKS
0	0	0	0	Prepared @ 0°F; maintained at 0°F for 3 days; temperature increased to 25°F; held at 25°F for 7 days.
100	2,060	28.9	10	
200	4,120	57.9	30	
300	6,180	86.8	40	
400	8,240	115.8	60	
500	10,300	144.7	68	
600	12,360	173.7	85	Stress at failure: 521 psi
700	14,420	202.6	94	
800	16,480	231.5	110	REM 1-6, 2-6 & 3-6 were formed from same material.
900	18,540	260.5	125	
1,000	20,600	289.4	135	
1,100	22,660	318.4	150	
1,200	24,720	347.3	173	
1,300	26,780	376.3	190	
1,400	28,840	405.2	270	
1,500	30,890	434.2	300	
1,600	32,960	463.1	320	
1,700	35,030	492.1	350	
1,800	37,090	521.0	380	

TABLE D-18 LAB-DATA AND RESULTS

SAMPLE: REM 2-6
DIMENSIONS: 5.85" x 5.78" x 8"
SHEARING AREA: 67.63 in^2
HORIZONTAL CONFINING PRESSURE: 50 psi

TEST TEMPERATURE: 25°F
DENSITY: 3.1 gm/cc.
MOISTURE CONTENT: 9.1%
LOADING RATE: 175 psi/min

LINE PRESSURE psi	SHEAR LOAD lb	SHEAR STRESS psi	VERTICAL DISPLACEMENT $x10^{-3}$ in	REMARKS
0	0	0	0	
250	5,150	76.1	20	Prepared at 0°F
500	10,300	152.3	55	maintained at 0°F for 3
750	15,450	228.4	75	days; temperature
1,000	20,600	304.6	95	increased to 25°F;
1,250	25,750	380.7	123	held at 25°F for 7 days.
1,500	30,900	456.9	153	Stress at failure:701 psi
1,750	36,050	533.0	193	
2,000	41,200	609.2	253	* - no reading taken
2,250	46,350	685.3	323	REM 1-6, 2-6 & 3-6 were
2,300	47,380	700.6	*	formed from same material.

TABLE D-19 LAB DATA AND RESULTS

SAMPLE: REM 3-6
DIMENSIONS: 5.915" x 5.675" x 8"
SHEARING AREA: 67.16 in^2
HORIZONTAL CONFINING PRESSURE: 100 psi

TEST TEMPERATURE: 25°F
DENSITY: 3.3 gm/cc.
MOISTURE CONTENT: 9.2%
LOADING RATE: *

LINE PRESSURE psi	SHEAR LOAD lb	SHEAR STRESS psi	VERTICAL DISPLACEMENT $x10^{-3}$in	REMARKS
0	0	0	0	
250	5,150	76.7	7	Prepared at 0°F
500	10,300	153.4	30	maintained at 0°F for 3
750	15,450	230.0	62	days; temperature
1,000	20,600	306.7	86	increased to 25°F;
1,250	25,750	383.4	121	held at 25°F for 7 days.
1,500	30,900	460.1	156	REM 1-6, 2-6 & 3-6 were
1,750	36,050	536.8	224	formed from same material.
2,000	41,200	613.5	336	
				Stress @ failure: 738 psi

*— no reading taken

TABLE D-20 LAB DATA AND RESULTS

SAMPLE: REM 4-6

TEST TEMPERATURE: 25°F

DIMENSIONS: 5.92" x 5.94" x 7.125"

DENSITY: 2.8 gm/cc.

SHEARING AREA: 70.35 in^2

MOISTURE CONTENT: 9.8%

HORIZONTAL CONFINING PRESSURE: 50 psi

LOADING RATE: 84 psi

LINE PRESSURE psi	SHEAR LOAD lb	SHEAR STRESS psi	VERTICAL DISPLACEMENT $x10^{-3}$ in	REMARKS
0	0	0	0	Sample remolded from
100	2,060	29.3	26	thawed fragments of
200	4,120	58.6	41	SAM 2-6.
300	6,180	87.8	61	
400	8,240	117.1	78	Prepared @ 0°F
500	10,300	146.4	88	maintained at 0°F for 3
600	12,360	175.7	104	days; temperature
700	14,410	204.9	121	increased to 25°F;
800	16,480	234.2	144	held at 25°F for 7 days.
900	18,540	263.5	162	* - no reading taken
1,000	20,600	292.8	196	
1,100	22,660	322.1	236	Stress @ failure: 337 psi
1,150	23,740	337.4	*	

TABLE D-21 LAB DATA AND RESULTS

SAMPLE: REM 5-6

DIMENSIONS: 5.88" x 5.875" x 8"

SHEARING AREA: 69.09 in^2

HORIZONTAL CONFINING PRESSURE: 100 psi

TEST TEMPERATURE: 25^0F

DENSITY: 2.5 gm/cc.

MOISTURE CONTENT: 3.4%

LOADING RATE: 140 psi/min

LINE PRESSURE psi	SHEAR LOAD lb	SHEAR STRESS psi	VERTICAL DISPLACEMENT $x10^{-3}$in	REMARKS
0	0	0	0	Sample remolded from thawed fragments of SAM 3-6
100	2,060	29.8	17	
200	4,120	59.6	42	Prepared @ 0^0F maintained at 0^0F for 3 days; temperature increased to 25^0F; held at 25^0F for 7 days. Stress @ failure: 417 psi
300	6,180	89.4	65	
400	8,240	119.3	83	
500	10,300	149.1	100	
600	12,360	178.9	116	
700	14,430	208.7	135	
800	16,480	238.5	153	
900	18,540	268.3	172	
1,000	20,600	298.2	190	
1,100	22,650	327.9	217	
1,200	24,720	357.3	252	
1,300	26,780	387.6	302	
1,400	28,840	417.4	352	

TABLE D-22 LAB DATA AND RESULTS

SAMPLE: REM 6-6

DIMENSIONS: 5.89" x 5.92" x 7.13"

SHEARING AREA: 34.87 in^2

HORIZONTAL CONFINING PRESSURE: 0 psi

TEST TEMPERATURE: 25^{o}F

DENSITY: 2.6 gm/cc.

MOISTURE CONTENT: 2.2%

LOADING RATE: *

	REMARKS
NO APPARENT STRENGTH RECORDED	Sample remolded from thawed fragments of SAM 1-6 Prepared @ 0^{o}F maintained at 0^{o}F for 3 days; temperature increased to 25^{o}F; held at 25^{o}F for 7 days. * - no reading taken

TABLE D-23 LAB DATA AND RESULTS

SAMPLE: REM 1-4

DIMENSIONS: 3.975" x 3.98" x 6.5"

SHEARING AREA: 31.64 in^2

HORIZONTAL CONFINING PRESSURE: 0 psi

TEST TEMPERATURE: 25^0F

DENSITY: 2.8 gm/cc.

MOISTURE CONTENT: 9.9%

LOADING RATE: 154 psi/min

LINE PRESSURE psi	SHEAR LOAD lb	SHEAR STRESS psi	VERTICAL DISPLACEMENT $x10^{-3}$in	REMARKS
0	0	0	0	Sample remolded from
50	1,030	32.5	19	thawed fragments of SAM 1-4
100	2,060	65.1	29	
150	3,090	97.7	51	Prepared @ 0^oF
200	4,120	130.2	71	maintained at 0^oF for 3
250	5,150	162.8	92	days; temperature
300	6,180	195.3	120	increased to 25^oF;
350	7,210	227.9	143	held at 25^oF for 7 days.
400	8,240	260.4	179	Stress @ failure: 309 psi
450	9,270	292.9	217	
475	9,790	309.3	*	* - no reading taken

TABLE D-24 LAB DATA AND RESULTS

SAMPLE: REM 2-4
DIMENSIONS: 4.00" x 3.805" x x 6.5"
SHEARING AREA: 30.44 in^2
HORIZONTAL CONFINING PRESSURE: 50 psi

TEST TEMPERATURE: 25^0F
DENSITY: 3.0 gm/cc.
MOISTURE CONTENT: 12.4%
LOADING RATE: *

LINE PRESSURE psi	SHEAR LOAD lb	SHEAR STRESS psi	VERTICAL DISPLACEMENT $x10^{-3}$ in
0	0	0	0
50	1,030	33.8	32
100	2,060	67.7	36
150	3,090	101.5	66
200	4,120	135.3	83
250	5,150	169.2	96
300	6,180	203.0	108
350	7,210	236.8	118
400	8,240	270.7	129
450	9,270	304.5	136
500	10,300	338.3	148
550	11,330	372.2	159
600	12,360	406.0	174
650	13,390	439.8	195
700	14,420	473.7	205
750	15,450	507.5	215
800	16,480	541.4	230
850	17,510	575.2	251
900	18,540	609.1	276
950	19,570	642.9	311

REMARKS

Sample remolded from thawed fragments of SAM 2-4

Prepared @ 0^oF maintained at 0^oF for 3 days; temperature increased to 25^oF; held at 25^oF for 7 days.
Stress @ failure: 643 psi

* - no reading taken

TABLE D-25 DATA AND RESULTS

SAMPLE: REM 3-4

DIMENSIONS: 3.775" x 3.975" x 6.5"

SHEARING AREA: 30.00 in^2

HORIZONTAL CONFINING PRESSURE: 100 psi

TEST TEMPERATURE: 25^{0}F

DENSITY: 3.0 gm/cc.

MOISTURE CONTENT: 10.1%

LOADING RATE: 200 psi/min

LINE PRESSURE psi	SHEAR LOAD lb	SHEAR STRESS psi	VERTICAL DISPLACEMENT x10^{-3}in	REMARKS
0	0	0	0	
50	1,030	34.3	10	Sample remolded from thawed fragments of SAM 3-4
100	2,060	68.7	27	
150	3,090	103.0	35	
200	4,120	137.3	45	
250	5,150	171.7	54	Prepared @ 0^{0}F maintained at 0^{0}F for 3 days; temperature increased to 25^{0}F; held at 25^{0}F for 7 days. Stress @ failure: 601 psi
300	6,180	206.0	66	
350	7,210	240.3	76	
400	8,240	274.7	85	
450	9,270	309.0	93	
500	10,300	343.3	104	
550	11,330	377.6	113	
600	12,360	412.0	124	
650	13,390	446.3	136	
700	14,420	480.7	154	
750	15,450	515.0	178	
800	16,480	549.3	200	* - no reading taken
850	17,510	583.7	221	
875	18,020	600.8	*	

TABLE D-26 LAB DATA AND RESULTS

SAMPLE: REM 4-4

DIMENSIONS: 3.965" x 3.78" x 7.5"

SHEARING AREA: 30.00 in^2

HORIZONTAL CONFINING PRESSURE: 0 psi

TEST TEMPERATURE: $25^{0}F$

DENSITY: 2.7 gm/cc.

MOISTURE CONTENT: 11.7%

LOADING RATE: 302 psi/min

LINE PRESSURE psi	SHEAR LOAD lb	SHEAR STRESS psi	VERTICAL DISPLACEMENT $x10^{-3}$ in	REMARKS
0	0	0	0	Sample remolded from thawed fragments of SAM 1-6
50	1,030	34.0	3	
100	2,060	68.6	7	
150	3,090	103.0	9	Prepared @ $0^{0}F$ maintained at $0^{0}F$ for 3 days; temperature increased to $25^{0}F$; held at $25^{0}F$ for 7 days. Stress @ failure: 704 psi
200	4,120	137.3	12	
250	5,150	171.7	14	
300	6,180	206.0	17	
350	7,210	240.3	19	
400	8,240	274.7	21	
450	9,270	309.0	23	
500	10,300	343.3	25	
550	11,330	377.7	30	
600	12,360	412.0	34	
650	13,390	446.3	37	
700	14,420	480.6	44	
750	15,450	515.0	50	
800	16,480	549.3	55	
850	17,510	583.7	64	
900	18,540	618.0	73	
950	19,570	652.3	83	
1,000	20,600	686.7	95	
1,025	21,110	703.8	105	

TABLE D-27 LAB DATA AND RESULTS

SAMPLE: REM 5-4

DIMENSIONS: 3.74" x 3.91" x 6.125"

SHEARING AREA: 29.25 in^2

HORIZONTAL CONFINING PRESSURE: 50 psi

TEST TEMPERATURE: 25°F

DENSITY: 2.9 gm/cc.

MOISTURE CONTENT: 9.2%

LOADING RATE: 160 psi/min

LINE PRESSURE psi	SHEAR LOAD lb	SHEAR STRESS psi	VERTICAL DISPLACEMENT $x10^{-3}$in	REMARKS
0	0	0	0	Sample remolded from
50	1,030	35.2	8	thawed fragments of
100	2,060	70.4	37	SAN 2-6, (same as REM 4-6)
150	3,090	105.6	62	
200	4,120	140.8	92	Prepared @ 0°F
250	5,150	176.1	130	maintained at 0°F for 3
300	6,180	211.3	180	days; temperature
350	7,210	246.5	206	increased to 25°F;
400	8,240	281.7	234	held at 25°F for 7 days.
450	9,270	316.9	289	Stress @ failure:317 psi

TABLE D-28 LAB DATA AND RESULTS

SAMPLE: REM 6-4

DIMENSIONS: 3.98" x 3.835" x 6.375"

SHEARING AREA: 30.53 in^2

HORIZONTAL CONFINING PRESSURE: 100 psi

TEST TEMPERATURE: 25^{0}F

DENSITY: 2.9 gm/cc.

MOISTURE CONTENT: 9.1%

LOADING RATE: *

LINE PRESSURE psi	SHEAR LOAD lb	SHEAR STRESS psi	VERTICAL DISPLACEMENT $x10^{-3}$in	REMARKS
0	0	0	0	
50	1,030	33.7	1	Sample remolded from thawed fragments of SAM 3-6 (same as REM 5-6)
100	2,060	67.5	4	
150	3,090	101.2	7	
200	4,120	134.9	13	
250	5,150	168.7	18	
300	6,180	202.4	23	
350	7,210	236.2	29	Prepared @ 0^{0}F maintained at 0^{0}F for 3 days; temperature increased to 25^{0}F; held at 25^{0}F for 7 days. Stress @ failure: 675 psi
400	8,240	269.9	34	
450	9,270	303.6	41	
500	10,300	337.4	47	
550	11,330	371.1	55	
600	12,360	404.8	64	
650	13,390	438.8	75	
700	14,410	472.3	86	
750	15,440	506.1	99	
800	16,480	539.8	121	
850	17,510	573.5	140	* - no reading taken
900	18,540	607.3	157	
950	19,570	641.0	185	
1,000	20,600	674.7	218	

TABLE D-29 LAB DATA AND RESULTS

SAMPLE: REM 1-2

DIMENSIONS: 1.975" x 1.89" x 8"

SHEARING AREA: 7.46 in^2

HORIZONTAL CONFINING PRESSURE: 0 psi

TEST TEMPERATURE: 25^{0}F

DENSITY: 2.6 gm/cc.

MOISTURE CONTENT: 12.4%

LOADING RATE: 415 psi

LINE PRESSURE psi	SHEAR LOAD lb	SHEAR STRESS psi	VERTICAL DISPLACEMENT x10^{-3}in.	REMARKS
0	0	0	0	Sample remolded from thawed fragments of SAM 1-6 (same as REM 4-4)
50	1,030	138.1	15	Prepared @ 0^{0}F
100	2,060	276.1	34	maintained at 0^{0}F for 3 days; temperature increased to 25^{0}F;
150	3,090	414.2	57	held at 25^{0}F for 7 days.
200	4,120	552.3	74	Stress @ failure: 552 psi

TABLE D-30 LAB DATA AND RESULTS

SAMPLE: REM 2-2

DIMENSIONS: 1.775" x 1.985" x 8"

SHEARING AREA: 7.05 in^2

HORIZONTAL CONFINING PRESSURE: 50 psi

TEST TEMPERATURE: 25°F

DENSITY: 2.7 gm/cc.

MOISTURE CONTENT: 6.3%

LOADING RATE: *

LINE PRESSURE psi	SHEAR LOAD lb	SHEAR STRESS psi	VERTICAL DISPLACEMENT $x10^{-3}$in	REMARKS
0	0	0	0	Sample remolded from thawed fragments of SAM 2-6 (same as REM 5-4)
50	1,030	146.1	28	
100	2,060	292.2	56	

Prepared @ 0°F; maintained at 0°F for 3 days; temperature increased to 25°F; held at 25°F for 7 days. Stress @ failure: 292 psi

* - no reading taken

TABLE D-31 LAB DATA AND RESULTS

SAMPLE: REM 3-2

DIMENSIONS: 1.97" x 1.84" x 8"

SHEARING AREA: 7.25 in^2

HORIZONTAL CONFINING PRESSURE: 100 psi

TEST TEMPERATURE: 25^{0}F

DENSITY: 2.6 gm/cc.

MOISTURE CONTENT: 11.3%

LOADING RATE: *

LINE PRESSURE psi	SHEAR LOAD lb	SHEAR STRESS psi	VERTICAL DISPLACEMENT $x10^{-3}$in	REMARKS
0	0	0	0	Sample remoulded from thawed fragments of SAM 3-6 (same as REM 6-4)
50	1,030	141.0	31	
75	1,540	212.1	*	

Prepared at 0^{o}F; maintained at 0^{o}F for 3 days; temperature increased to 25^{o}F; held at 25^{o}F for 7 days.

Stress @ failure: 212 psi

* - no reading taken

APPENDIX E

TABLES and GRAPHS

GRAIN SIZE ANALYSIS

TABLE E-1 - GRAIN SIZE ANALYSIS

SAMPLE: REM 1-6

WEIGHT OF SAMPLE: 500 gm

U.S. SIEVE NUMBER	TYLER MESH	SIEVE OPENING (mm)	WEIGHT OF SIEVE (gm)	WT. SIEVE + SOIL (gm)	WT. SOIL RETAINED (gm)	PERCENT RETAINED	CUMULATIVE PERCENT RETAINED	PERCENT FINER
4	4	4.76	539.4	580.4	41.0	8.20	8.20	91.8
8	8	2.38	531.8	550.7	18.9	3.78	11.98	88.02
16	16	1.19	453.8	484.5	30.7	6.14	18.12	81.88
30	28	.595	408.4	467.9	59.5	11.90	30.02	69.98
50	48	.297	421.4	496.4	75.0	15.00	45.02	54.98
70	65	.210	363.3	400.0	36.7	7.34	52.36	47.64
100	100	.149	354.5	387.4	32.9	6.58	58.94	41.06
200	200	.074	338.2	411.2	73.0	14.60	73.54	26.46
325	325	.044	329.4	408.0	78.6	15.72	89.26	10.74
400	400	.037	387.7	438.4	50.7	10.14	99.40	.60
PAN	-	-	376.1	379.1	3.0	.60	100.00	-

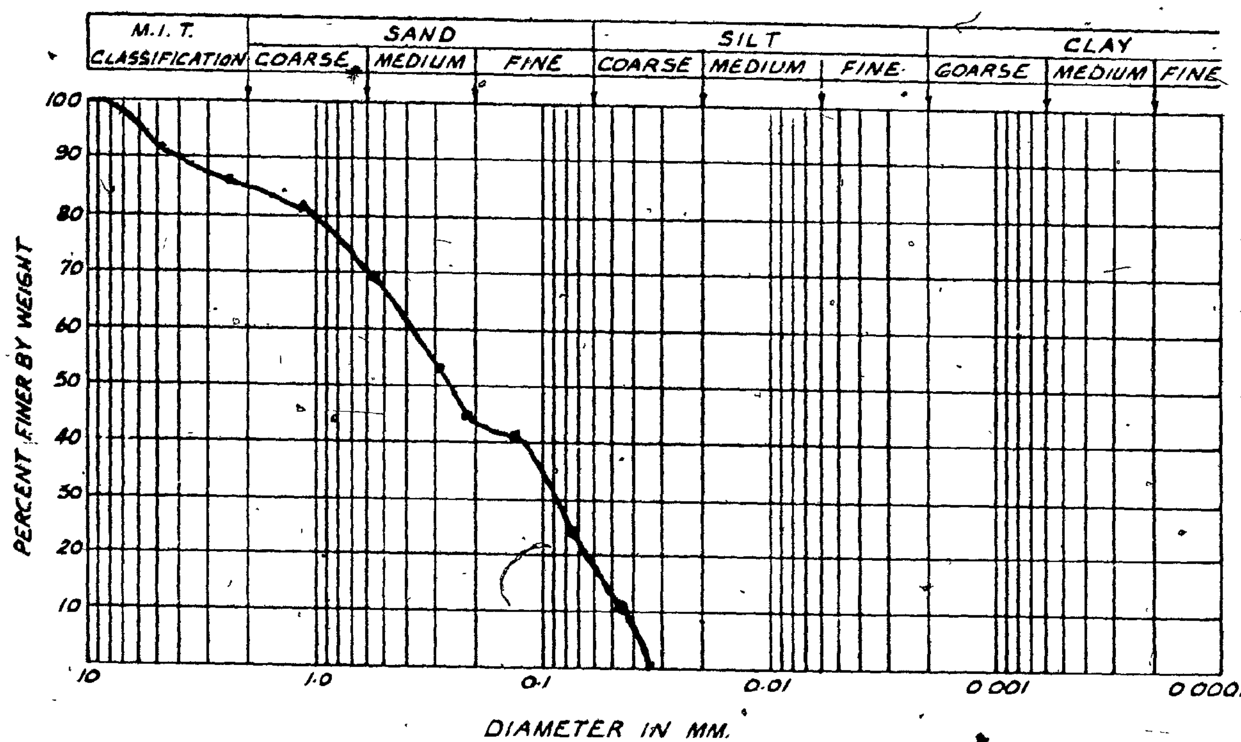


FIGURE E-1 GRAIN SIZE ANALYSIS

REM 1-6

TABLE E-2 GRAIN SIZE ANALYSIS

SAMPLE: SAM 1-6

WEIGHT OF SAMPLE: 500 gm

U.S. SIEVE NUMBER	TYLER MESH	SIEVE OPENING (mm)	WEIGHT OF SIEVE (gm)	WT. SIEVE + SOIL (gm)	WT. SOIL RETAINED (gm)	PERCENT RETAINED	CUMULATIVE PERCENT RETAINED	PERCENT FINER
4	4	4.76	539.2	585.5	46.3	9.27	9.37	90.73
8	8	2.38	531.8	559.2	27.4	5.48	14.75	85.25
16	14	1.19	453.8	485.8	32.0	6.41	21.16	78.84
30	28	.595	408.4	466.8	58.4	11.68	32.84	67.16
50	48	.297	421.4	492.0	70.6	14.13	46.97	53.03
70	65	.210	362.9	397.2	34.3	6.86	53.83	46.17
100	100	.149	354.4	386.4	32.0	6.40	60.23	39.77
200	200	.074	338.2	405.5	67.3	13.47	73.70	26.30
325	325	.044	329.3	412.5	83.2	16.65	90.35	9.65
400	400	.037	387.7	433.4	45.7	9.14	99.49	.51
PAN	-	-	376.1	378.5	2.4	.48	99.97	-

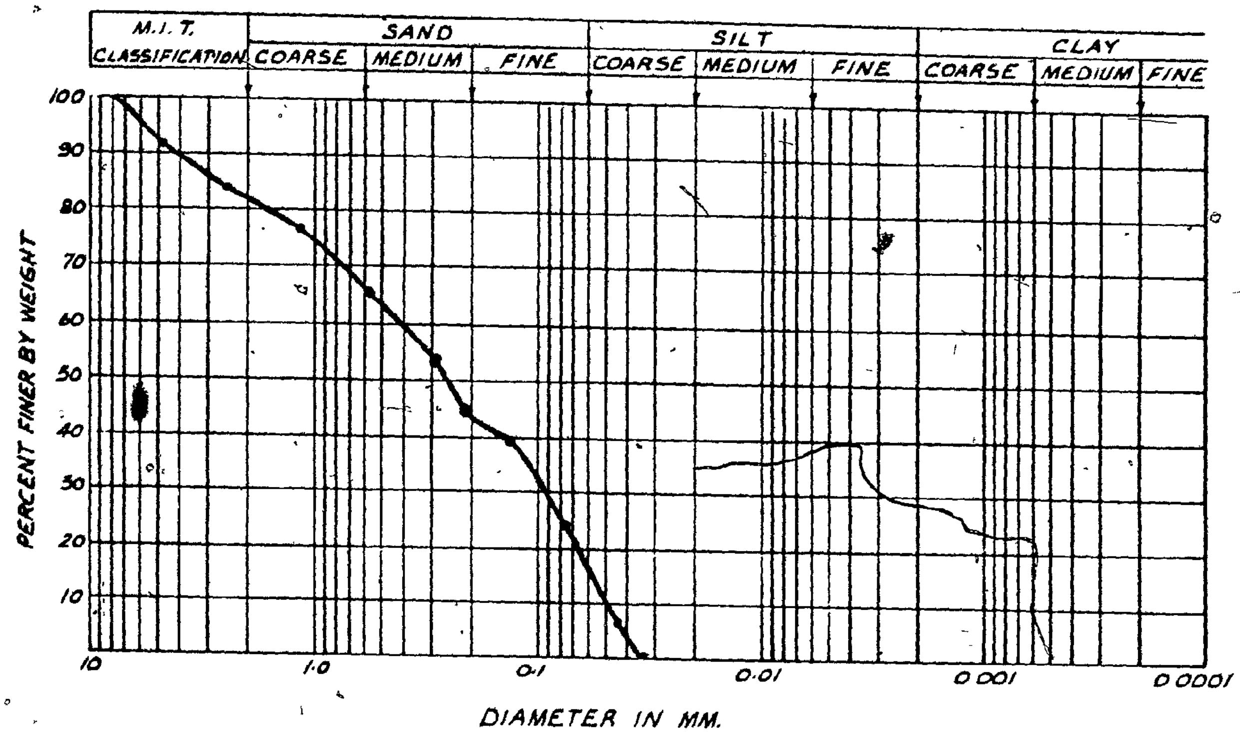


FIGURE E-2 GRAIN SIZE ANALYSIS

SAM 1-6

TABLE E-3 GRAIN SIZE ANALYSIS

SAMPLE: SAM 2-6

WEIGHT OF SAMPLE: 500 gm.

U.S. SIEVE NUMBER	TYLER MESH	SIEVE OPENING (mm)	WEIGHT OF SIEVE (gm)	WT. SIEVE + SOIL (gm)	WT. SOIL RETAINED (gm)	PERCENT RETAINED	CUMULATIVE PERCENT RETAINED	PERCENT FINER
4	4	4.76	539.0	539.7	0.7	.14	.14	99.86
8	8	2.38	531.6	544.1	12.5	2.50	2.64	97.36
16	14	1.19	453.7	484.2	30.5	6.11	8.75	91.25
30	28	.595	408.5	454.8	46.3	9.27	18.02	81.98
50	48	.297	421.4	501.9	80.5	16.13	34.15	65.85
70	65	.210	362.9	409.5	46.6	9.33	43.48	56.52
100	100	.149	354.3	397.0	42.7	8.55	52.03	48.00
200	200	.074	338.2	420.5	82.3	16.49	68.52	31.48
325	325	.044	329.3	376.6	47.3	9.48	78.00	22.00
400	400	.037	387.7	404.7	17.0	3.41	81.41	18.59
PAN	-	-	376.0	468.8	92.8	18.60	100.01	-

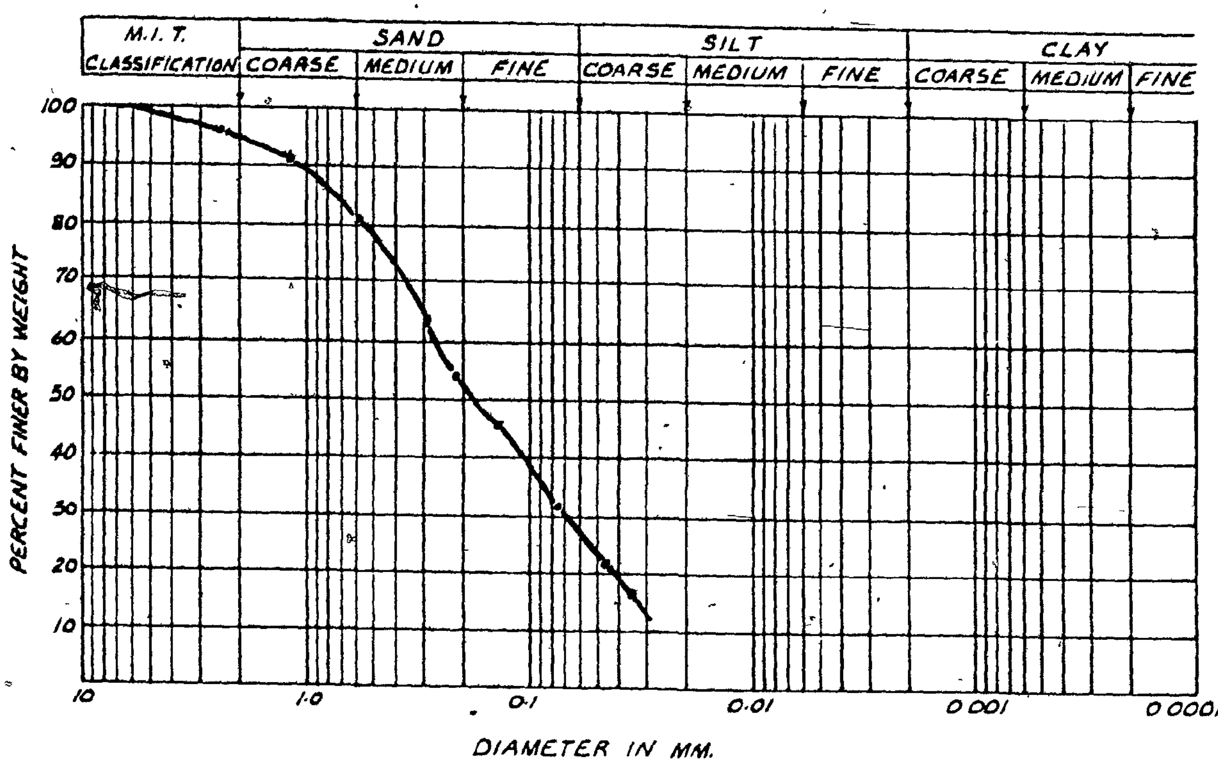


FIGURE E-3 GRAIN SIZE ANALYSIS
SAM 2-6

TABLE E-4 GRAIN SIZE ANALYSIS

SAMPLE: SAM 3-6

WEIGHT OF SAMPLE: 500 gm

U.S. SIEVE NUMBER	TYLER MESH	SIEVE OPENING (mm)	WEIGHT OF SIEVE (gm)	WT. SIEVE + SOIL (gm)	WT. SOIL RETAINED (gm)	PERCENT RETAINED	CUMULATIVE PERCENT RETAINED	PERCENT FINER
4	4	4.76	539.1	541.7	2.6	.52	.52	99.48
8	8	2.38	531.5	539.1	7.6	1.52	2.04	97.96
16	14	1.19	453.6	467.3	13.7	2.74	4.78	95.22
30	28	.595	408.4	452.2	43.8	8.76	13.54	86.46
50	48	.297	421.4	496.8	75.4	15.08	28.62	71.38
70	65	.210	362.8	401.3	38.5	7.70	36.32	63.68
100	100	.149	354.4	391.8	37.4	7.48	43.80	56.20
200	200	.074	338.3	424.0	85.7	17.14	60.94	39.06
325	325	.044	329.4	391.1	61.7	12.34	73.28	26.72
400	400	.037	387.7	409.8	22.1	4.42	77.70	22.30
PAN	-	-	375.9	487.4	111.5	22.30	100.00	-

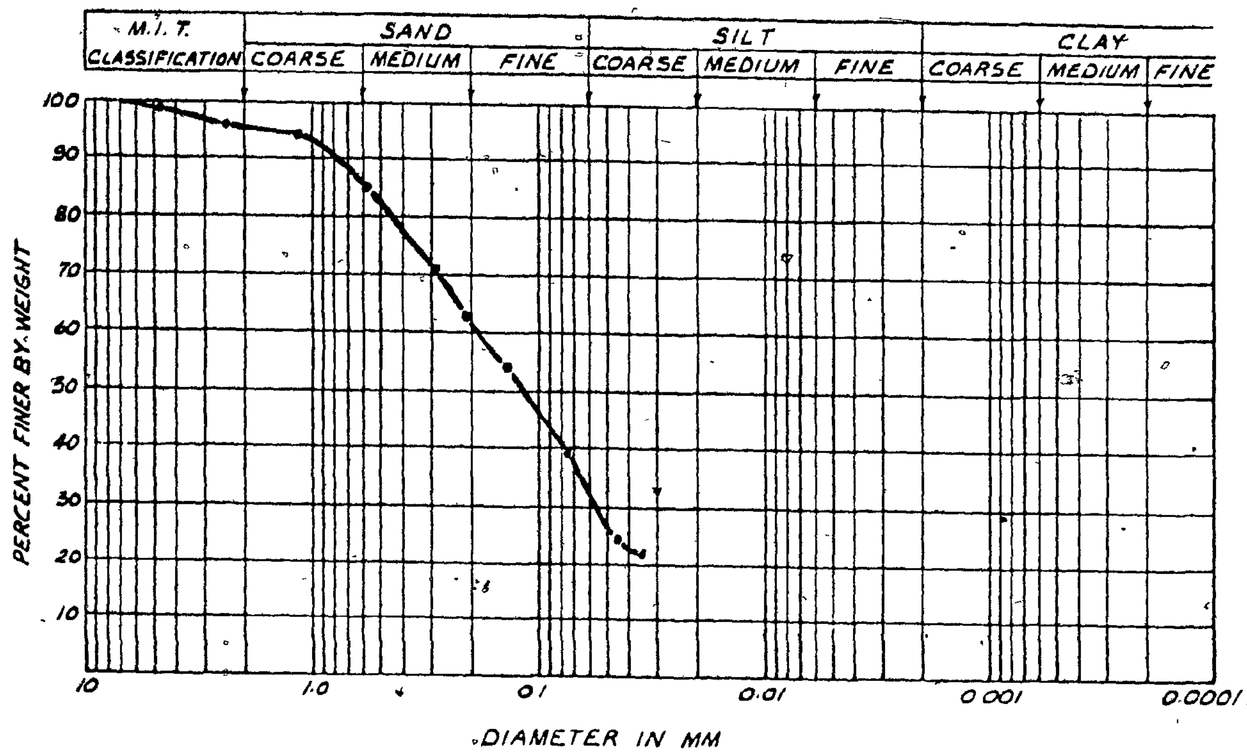


FIGURE E-4 GRAIN SIZE ANALYSIS
SAM 3-6

TABLE E-5 GRAIN SIZE ANALYSIS

SAMPLE: SAN 1-4

WEIGHT OF SAMPLE: 250 gm

U.S. SIEVE NUMBER	TYLER MESH	SIEVE OPENING (mm)	WEIGHT OF SIEVE (gm)	WT. SIEVE + SOIL (gm)	WT. SOIL RETAINED (gm)	PERCENT RETAINED	CUMULATIVE PERCENT RETAINED	PERCENT FINER
4	4	4.76	539.2	539.2	0	-	0	-
8	9	2.38	531.7	531.8	.1	.04	.04	99.96
16	14	1.19	453.8	455.3	1.5	.60	.64	99.36
30	28	.595	408.5	424.2	15.7	6.27	6.91	93.09
50	48	.297	421.6	455.3	33.7	13.47	20.38	79.62
70	65	.210	362.9	387.0	24.1	9.63	30.01	69.99
100	100	.149	354.4	378.7	24.3	9.71	39.72	60.28
200	200	.074	338.5	391.7	53.2	21.26	60.98	39.02
325	325	.044	329.5	376.5	47.0	18.78	79.76	20.24
400	400	.037	387.7	401.4	13.7	5.47	85.23	14.77
PAN	-	-	376.1	413.0	36.9	14.75	100.00	-

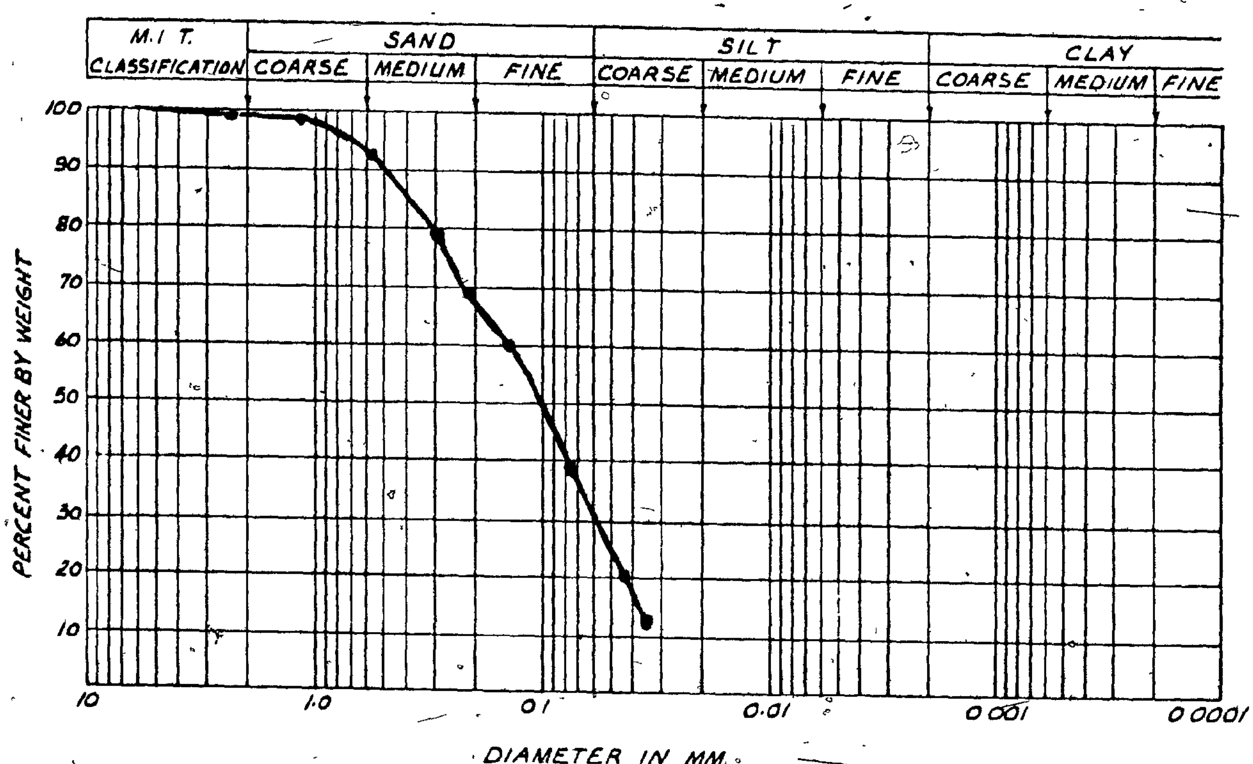


FIGURE E-5 GRAIN SIZE ANALYSIS
SAM 1-4

TABLE E-6 GRAIN SIZE ANALYSIS

SAMPLE: SAM 2-4

WEIGHT OF SAMPLE: 250 gm

U.S. SIEVE NUMBER	TYLER MESH	SIEVE OPENING (mm)	WEIGHT OF SIEVE (gm)	WT. SIEVE + SOIL (gm)	WT. SOIL RETAINED (gm)	PERCENT RETAINED	CUMULATIVE PERCENT RETAINED	PERCENT FINER
4	4	4.76	539.2	539.2	0	0	0	100.00
8	8	2.38	531.6	531.6	0	0	0	100.00
16	14	1.19	453.8	451.4	3.6	1.44	1.44	98.56
30	28	.595	408.4	446.0	37.6	15.05	16.49	83.51
50	48	.297	421.6	455.9	34.3	13.73	30.22	69.78
70	65	.210	363.0	380.4	17.4	6.96	37.18	62.82
100	100	.149	354.5	370.1	15.6	6.24	43.42	56.58
200	200	.074	338.5	372.8	34.3	13.73	57.15	42.85
325	325	.044	329.5	377.9	48.4	19.38	76.53	23.47
400	400	.037	367.8	432.6	44.8	17.93	94.46	5.54
PAN	-	-	364.8	378.6	13.8	5.52	100.00	-

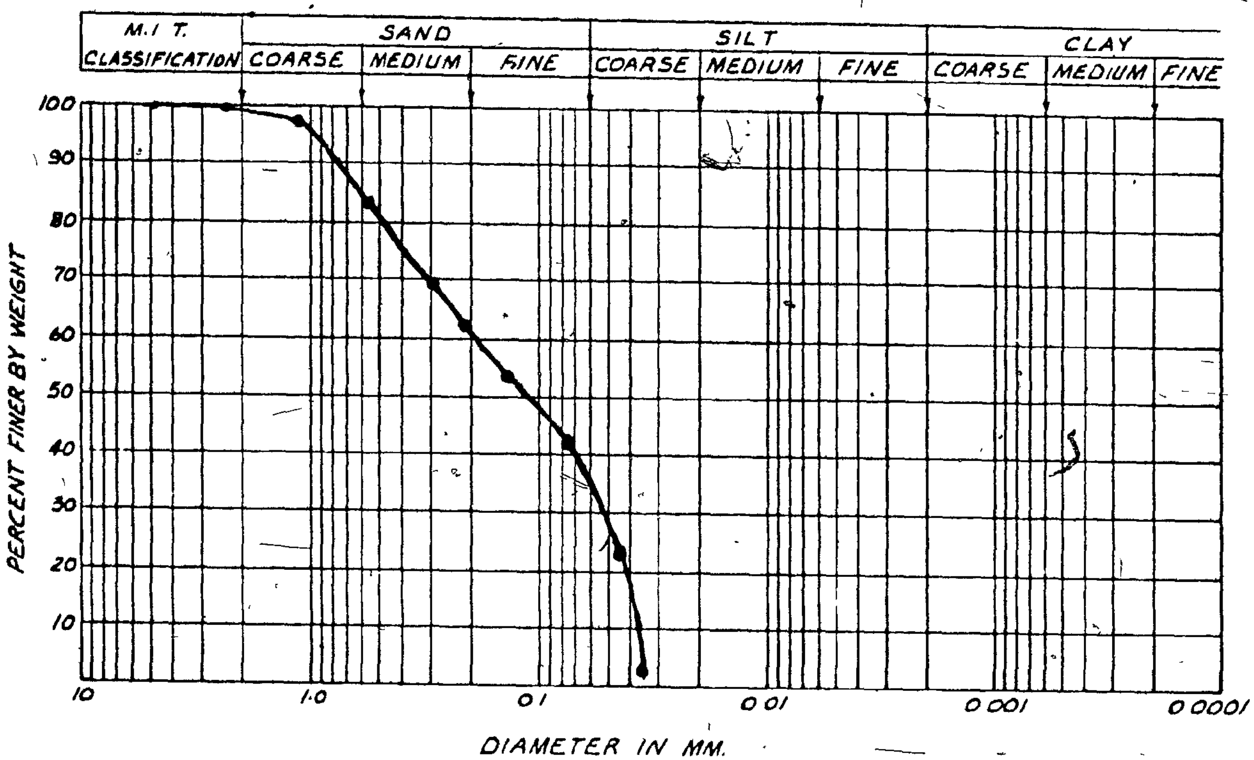


FIGURE E-6 GRAIN SIZE ANALYSIS
SAM 2-4

TABLE E-7 GRAIN SIZE ANALYSIS

SAMPLE: SAN 3-4

WEIGHT OF SAMPLE: 250 gm

U.S. SIEVE NUMBER	TYLER MESH	SIEVE OPENING (mm)	WEIGHT OF SIEVE (gm)	WT. SIEVE + SOIL (gm)	WT. SOIL RETAINED (gm)	PERCENT RETAINED	CUMULATIVE PERCENT RETAINED	PERCENT FINER
4	4	4.76	539.1	539.1	0	0	0	100.00
8	8	2.38	531.4	532.6	1.2	.48	.48	99.52
16	14	1.19	453.8	454.9	1.1	.44	.92	99.08
30	28	.595	408.5	420.3	11.8	4.72	5.64	94.36
50	48	.297	421.5	450.3	28.8	11.54	17.18	82.82
70	65	.210	362.9	384.5	21.6	8.66	25.84	74.16
100	100	.149	354.4	377.3	22.9	9.18	35.02	64.98
200	200	.074	338.5	390.3	51.8	20.76	55.78	44.22
325	325	.044	329.6	365.5	35.9	14.39	70.17	29.83
400	400	.037	387.8	402.7	14.9	5.97	76.14	23.86
PAN	-	-	364.7	424.2	59.5	23.84	100.00	-

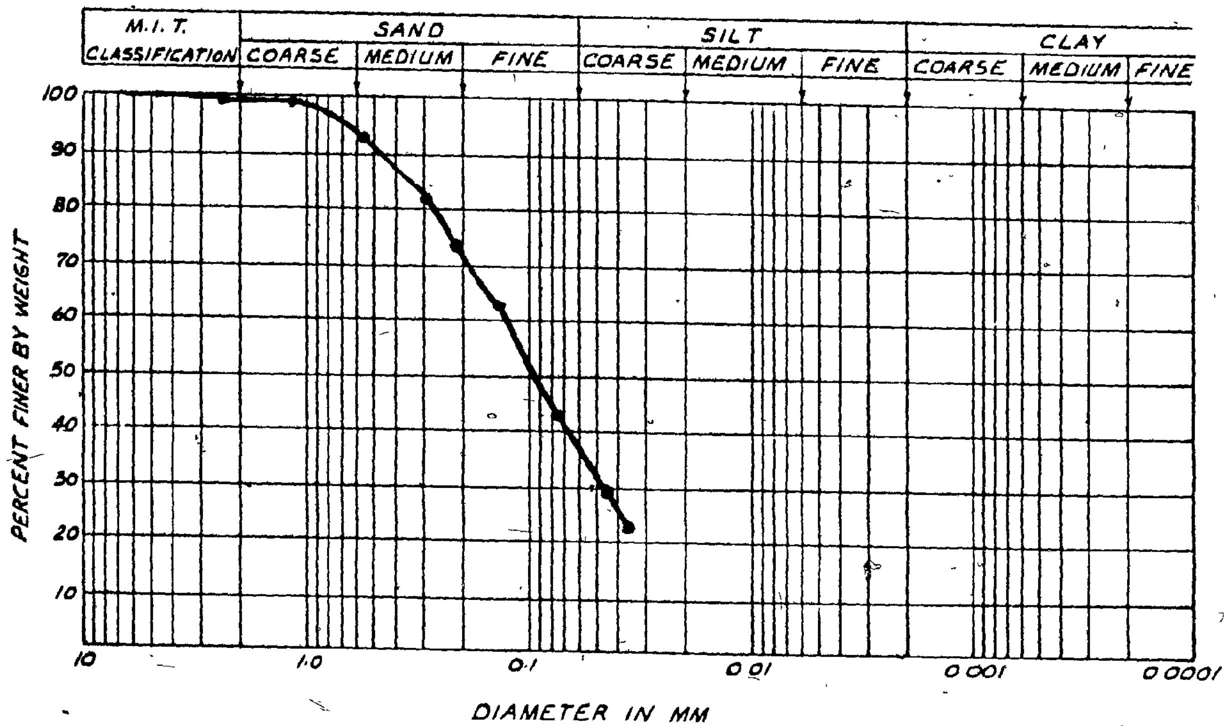


FIGURE E-7 GRAIN SIZE ANALYSIS
SAM 3-4

APPENDIX F

SCHEFFERVILLE TESTS:
GRAIN SIZE ANALYSIS

TABLE F-1 SCHEFFERVILLE TESTS: SHEAR TEST DATA

SAMPLE: Middle Iron Formation

RATE: 0.090 in/min — AREA = 6" x 6"

NORMAL CONFINING PRESSURE: 100 psi — TEMPERATURE: 70°F

SHEAR DISPLACEMENT in	LOAD READING	SHEAR LOAD lb	REMARKS
0	0	0	
.050	33	767	Using Proving Ring # 3964 and a conversion factor of 23.25 lb/division.
.150	53	1232	
.200	61	1418	
.250	68	1581	
.300	72	1674	Shear stress at failure: 57 psi
.350	74	1720	
.400	77	1790	
.450	78	1813	
.550	79	1837	
.650	80	1860	
.750	80	1860	
.950	81	1883	
1.150	82	1906	
1.250	83	1930	
1.350	84	1953	
1.450	85	1976	
1.550	86	19999	
1.650	86	19999	
1.750	87	2023	
1.850	87	2023	
1.950	88	2046	
2.050	87	2023	
2.150	87	2023	

TABLE F-2 SCHEFFERVILLE TESTS: SHEAR TEST DATA

SAMPLE: Middle Iron Formation
RATE: 0.090 in/min
NORMAL CONFINING PRESSURE: 100 psi

AREA = 6" x 6"
TEMPERATURE: 70^{o}F

SHEAR DISPLACEMENT in	LOAD READING	SHEAR LOAD lb	REMARKS
0	0	0	
.10	45	1046	Using Proving Ring # 3964 and a conversion factor of 23.25 lb/division
.15	58	1348	
.20	66	1534	
.25	72	1674	
.30	75	1744	
.35	77	1790	Shear stress at failure: 51 psi
.40	78	1813	
.45	78	1813	
.50	78	1813	
.60	78	1813	
.70	79	1837	
.80	79	1837	
.90	79	1837	
1.00	79	1837	
1.10	79	1837	
1.20	79	1837	
1.30	79	1837	
1.40	78	1813	
1.50	77	1790	
1.60	76	1767	
1.70	75	1744	
1.80	75	1744	
1.90	75	1744	

TABLE F-3 SCHEFFERVILLE TESTS: SHEAR TEST DATA

SAMPLE: Middle Iron Formation
RATE: 0.090 in/min
NORMAL CONFINING PRESSURE: 200 psi
AREA = 6" x 6"
TEMPERATURE: 70^{o}F

SHEAR DISPLACEMENT in	LOAD READING	SHEAR LOAD lb	REMARKS
0	0	0	
.03	55	1279	Using Proving Ring # 3964 and a conversion factor of 23.25 lb/division.
.06	77	1790	
.09	92	2139	
.11	99	2302	
.14	111	2581	
.21	139	3232	Shear stress at failure: 111 psi
.24	147	3418	
.29	158	3673	
.34	164	3813	
.37	166	3859	
.39	167	3883	
.44	167	3883	
.54	168	3906	
.64	168	3906	
.74	169	3929	
.84	170	3953	
.94	170	3953	
1.14	169	3929	
1.24	169	3929	
1.44	168	3906	
1.54	168	3906	
1.64	167	3883	
1.74	165	3836	
1.84	162	3766	
1.94	158	3673	
1.04	156	3627	
2.14	155	3604	
2.24	154	3580	

TABLE F-4 SCHEFFERVILLE TESTS: SHEAR TEST DATA

SAMPLE: Middle Iron Formation
RATE: 0.090 in/min
NORMAL CONFINING PRESSURE: 400 psi

AREA = 6" x 6"
TEMPERATURE: 70^{o}F

SHEAR DISPLACEMENT in	LOAD READING	SHEAR LOAD lb	REMARKS
0	0	0	
.037	80	1860	Using Proving Ring
.070	200	4650	# 3964 and a conver-
.110	250	5812	sion factor of
.170	300	6975	23.25 lb/division.
.225	330	7672	
.310	342	7952	Shear stress at
.360	342	7952	failure: 222 psi.
.410	342	7952	
.460	341	7928	
.510	340	7905	
.560	340	7905	
.610	339	7882	
.910	330	7672	
1.110	322	7486	
1.310	312	7254	

TABLE F-5 GRAIN SIZE ANALYSIS

SAMPLE: SCHEFFERVILLE TEST-
MIDDLE IRON FORMATION

WEIGHT OF SAMPLE: 500 gm

U.S. SIEVE NUMBER	TYLER MESH	SIEVE OPENING (mm)	WEIGHT OF SIEVE (gm)	WT. SIEVE + SOIL (gm)	WT. SOIL RETAINED (gm)	PERCENT RETAINED	CUMULATIVE PERCENT RETAINED	PERCENT FINER
16	14	1.410	823.2	828.5	5.3	1.06	1.06	98.94
60	60	0.250	710.2	845.8	135.6	27.12	28.18	71.82
80	80	0.177	704.5	742.4	37.9	7.58	35.76	64.24
140	150	0.104	716.6	774.6	58.0	11.63	47.39	52.61
200	200	0.074	702.6	743.5	40.9	8.18	55.57	44.43
270	270	0.053	698.6	732.6	34.0	6.79	62.36	37.64
325	325	0.044	696.8	736.3	39.5	7.89	70.25	29.75
PAN	-	-	680.4	843.7	148.8	29.75	100.00	-

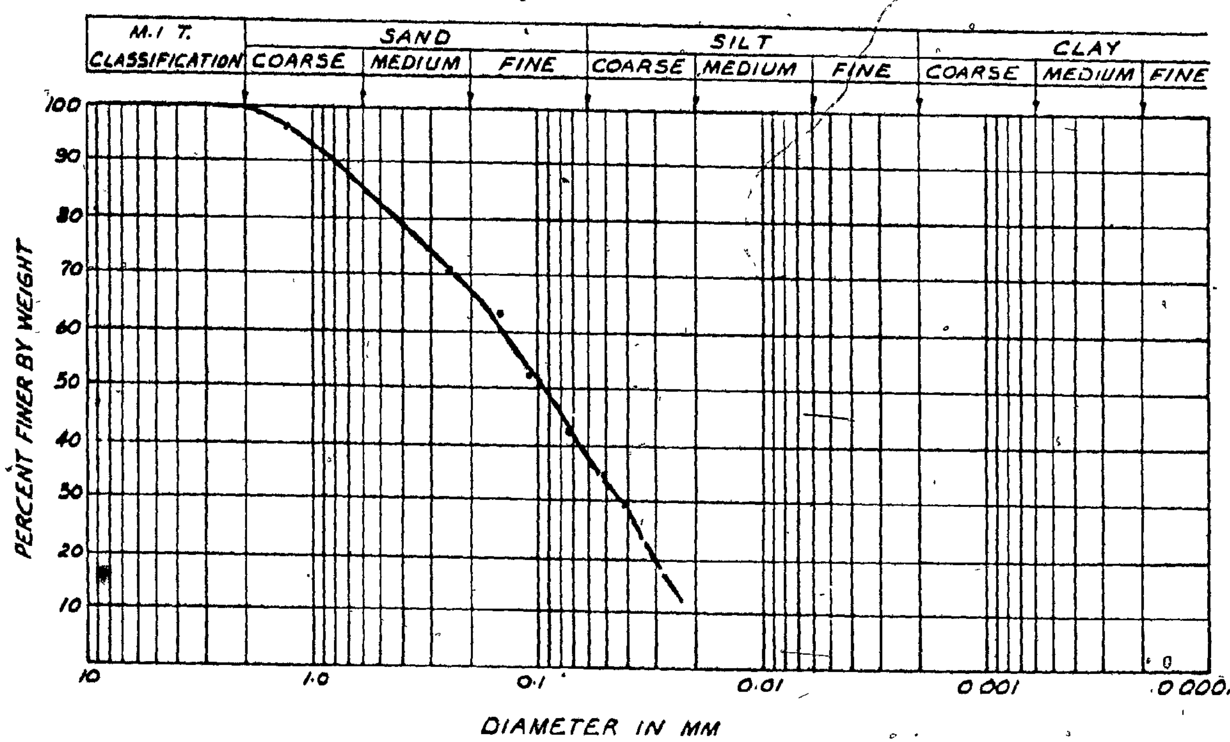


FIGURE F-1 GRAIN SIZE ANALYSIS
SCHEFFERVILLE TEST - MIF