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ABSTRACT

Frost action in soils has long been recognized as a major factor affecting both military and civilian construction in freezing climates. As a better understanding of the mechanism of frost action in soils is achieved, the importance of the pore size distribution of the freezing soil has become apparent. Considerations of pore size are shown to have a direct bearing on frost susceptibility criteria for soils. Frost heaving pressures in soils have also been successfully correlated with pore size considerations. It is also shown that the influence of applied pressure on frost action implies a dependence of frost susceptibility criteria on the depth of frost penetration.

A knowledge of the shear strength properties of frozen soils is becoming increasingly important due to the growth of applications of soil freezing for design and construction purposes. The ice content of a frozen soil is directly related to its short-term shear strength. The ice content in turn can be correlated with the moisture potential of the pore water in the soil. Studies of the stress-strain-time properties of frozen soils are being undertaken, employing torsion tests on hollow cylindrical samples.

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INTRODUCTION

Frost action in soils has important implications in both military and civilian construction. While most results of frost action are detrimental, there is a growing field of applications where the freezing of soils is utilized to advantage, either as a construction expedient or even for some permanent facility.

When so-called "frost-susceptible" soil freezes under the proper circumstances relating to supply of water, etc., the formation of ice lenses is a well-known phenomenon. These lenses create heaving pressures during their formation which, unless counteracted, will cause heave of the frozen surface. Upon thawing, the water released from these ice lenses will cause local over-saturation until the excess water can leave the thawed zone. Since thawing commences from the surface and progresses downwards, the frozen zone underlying the initially thawed zone acts as an impervious diaphragm, tending to trap the excess water in this upper layer. Until the frost has completely thawed, a condition of "super-saturation" exists in frost-susceptible soils which is characterized by dramatic losses of strength. Seasonal loss of supporting ability of road and airfield surfaces is a well-known example of this effect.

From a design and construction standpoint, it is important to be able to recognize which soils are frost susceptible, i.e., subject to the formation of ice lenses in sufficient number and of appreciable thickness to produce detrimental heave effects and to be subject to seasonal loss of strength. While it has been long understood that silt soils are the most frost susceptible, an exact criterion to determine to what degree a given soil will be frost susceptible, particularly "border-line" cases so often encountered in natural soils, has not yet been established. The question of criteria of frost susceptibility has been examined recently by several Canadian researchers, and their findings will be discussed in this paper.

Of equal importance in a design situation, is the ability to predict the magnitude of heaving pressures generated in soils upon freezing. If a knowledge of such pressures is available, suitable allowance could be made for them in design, by the application of a suitable surcharge pressure. This problem is also being actively studied in Canada at the moment and some recent results are presented herein.

To date, the adverse effects of frost action in soils have received most of the engineers' attention and little research has been directed towards the beneficial effects of freezing. However, there is an increasing awareness that some of the properties of frozen soils can be exploited in design and construction. The construction of frozen diaphragms to control ground-water seepage into excavations, shafts, tunnels, etc., is now a well-established practice. The storage of liquified gasses in underground containers is becoming more common. Also, the increased strength of frozen soils can be utilized as a means of increasing the stability of the slope of an excavation or cutting. As more and more applications of frozen soils are attempted, a knowledge of the engineering properties of frozen soils will assume a position of increasing importance. An extensive study of the properties of frozen soils has been under way at McGill University for many years. The paper concludes with a brief discussion of some of the more important properties of frozen soils which have been disclosed by this study.

THE MECHANISM OF FROST ACTION IN SOILS

A brief discussion of the mechanism of frost action in soils is necessary for an understanding of the complexities involved in establishing a frost susceptibility criterion which will distinguish within narrow limits between those soils which will be acceptable for some specific purpose and those which will not be suitable. Frost action as used here means the formation of distinct layers or lenses of crystalline ice in an originally intact soil which has been subjected to a subfreezing temperature for an extended period under suitable conditions of accessibility to a supply of ground water. It is important to recognize that the proper conditions of temperature and water supply are necessary to cause frost action in soils, as well as the type of soil involved. However, within the usual economic limitations there is very little which can be done to control the two former factors, while variation of the latter, the soil actually considered for use at a specific location, can often be achieved either by replacement or modification. For this reason, frost susceptibility criteria generally apply to the type of soil only.

A typical soil in-situ is a complex three-phase system consisting of air, water and solid particles. Due to interactions between the water and the surfaces of the solid particles, water is attracted to the particle surfaces. In the case of the larger sized soil particles, such as sand and silt, the predominant soil-water interaction is one of adsorption. In unsaturated soils, curved meniscii form at the air-water interfaces due to a combination of adsorptive forces and the surface tension of the water. The radii of the menisci will be influenced by the pore sizes; the height of capillary rise of water in soil above a phreatic surface is directly related to the pore sizes encountered.

In the case of clays, where the particles carry distinctive electrical charges and have associated with them various metallic cations to assure their electrical neutrality in the dry state, the surface interaction is far more complex, involving not only adsorption and hydrogen bonding but also the interrelated phenomenon of the hydration of the cations. The cations surrounding a wetted clay particle tend to leave the surface and form a diffuse layer around the particle; the presence of this concentration of ions around each particle creates an osmotic potential between the ion swarms close to the particle (in the so-called "bound water" or "double layer") and the exterior or bulk water.

Water in soils is therefore subject to various potentials, which will control its behaviour when subjected to subfreezing temperatures. Briefly, these potentials are:

1. the osmotic potential, arising from differences in the solute concentration between the soil water and the bulk water;
2. the matric potential, caused by adsorptive and surface tension forces tending to hold the water to the soil;
3. the gravitational potential, which is due to the difference in position or head between the soil water and free water, and,

4. any potential due to external gas pressure.

Since freezing of the surface layer of soil is generally restricted to the upper four to seven feet of soil, the gravitational potential is generally small compared to the former two. The case of excess external gas pressure will be ignored.

Consider now a soil-air-water system through which a freezing front is advancing. The ice front will encounter restrictions in the form of the soil pores and will be forced to form a curved face to advance into the pore. This immediately sets up a condition of temperature depression which can be shown to be inversely related to the radius of the curved ice front, which in turn is related to the pore size. By lowering the temperature at which water freezes to ice, the advance of the ice front under some temperature gradient is temporarily halted at a given size of constriction. However, due to the influence of the matric and/or osmotic potentials in the soil water, the water closest to the particle surfaces has a lower freezing point than that of bulk water. Thus, in regions adjacent to soil particles, unfrozen water can exist in contact with the ice front. It is generally agreed that some portion of the water film surrounding the particles tends to freeze, causing the ice crystal to grow while remaining in a stationary position. Other water from the lower unfrozen zone is drawn to the ice front to satisfy the attraction of the particles for water; this is often referred to as a suction caused by the freezing process. To support this mechanistic picture of frost action, Penner (1959) has demonstrated that the tension or suction in the soil moisture in a closed system increases as freezing progresses until an upper limit is reached where a combination of decrease in unsaturated permeability and the lowered freezing point of the increasingly stressed water combine to arrest the growth of ice crystals.

The above assumes that the ice lenses can grow unimpeded by external constraints. In a freezing soil deposit there will always be some overburden pressure to overcome to create a space for the growing ice lens. Where a structure is founded on the soil, additional pressure will be exerted on the soil. The application of pressure to the ice lenses will also result in a temperature depression and, thus, the application of external constraints will also influence frost action in soils. If a sufficient pressure is applied, the formation of ice lenses can be arrested; this phenomenon can be demonstrated in the laboratory and the maximum pressure so required is termed the "heaving pressure".

The mechanism discussed is therefore dependent on four interrelated factors which combine to control the rate of frost heave in a soil:

1. the pore size which influences the curvature of the advancing ice front;
2. the particle size, mineralogical composition, disolved solutes and free electrolytes which influence the moisture potential;
3. the permeability, which will affect the rate at which water will flow to the freezing front in response to the suction set up by the freezing process; and,

4. overburden pressure plus surcharge pressures and/or suction or capillary stresses in the water which will influence the pressure at the ice-water interface.

While the moisture potential is far greater in clays than in silts, the much lower permeability of clays tends to limit the supply of water reaching the freezing zone in some finite time, such as a freezing season. Sands, on the other hand, have low moisture potentials, particularly if they are nearly saturated so that capillary stresses are small. Nearly all of the water in sands has, therefore, properties approaching those of bulk water and so a freezing front advances through sand by causing uniform freezing without the growth of ice lenses. Silts have the right combination of moisture potential and permeability to cause the most significant frost effects.

The aim of frost susceptibility criteria has therefore been largely directed to identifying soils with a critical silt concentration which will create optimum frost action effects, recognizing that sands and clays will not display detrimental frost effects under most normal circumstances.

At the same time, considerable interest has been displayed in the prediction of maximum heaving pressures in soils of known gradation and density. The ability to predict heaving pressures can be used to prevent damage to earth embankments subject to freezing by the application of sufficient surcharge to prevent ice lensing. A knowledge of the magnitude of heaving pressures beneath foundations would also enable the performance of rational designs to prevent uplift and the resulting structural distress.

FROST SUSCEPTIBILITY CRITERIA

A comprehensive review of frost susceptibility criteria up to 1961 has been made by Townsend and Csathy (1963a). Most of the criteria presented are given in terms of limiting grain size distributions or, in some cases, in terms of groupings in an appropriate soil classification system; such classification systems rely to a major extent on grain size distribution to select the various soil groups.

By far the most commonly used criterion for frost susceptibility is that of Casagrande (1931) which is based on field and laboratory studies dating back to 1927. The Casagrande criterion has been expanded somewhat since it was first published. In its present form it is employed by the U.S. Army Corps of Engineers and other large agencies. Stated briefly, the criterion says that well-graded soils which contain more than three percent by weight of particles finer than 0.02 mm will be frost susceptible while for uniform soils the amount of material finer than 0.02 mm can be as great as 10 percent before the soil will be frost susceptible.

As pointed out by Penner (1959), theory suggests that pore size is more important in establishing frost susceptibility than grain size, although the two factors are obviously related. Pore sizes are larger in uniformly graded soils and it is interesting to note that the Casagrande criterion allows for a larger amount of minus 0.02 mm material in uniform soils; this obviously recognizes the influence of pore size. Beskow (1935) in his classic work on soil freezing and frost heaving, established a relationship between capillarity and frost susceptibility for both moraine soils (well-graded) and sediments (uniformly graded). "Capillarity" as used by Beskow was the maximum height which a column of water in contact with a wet soil could be raised in a tensiometer. The concept of Beskow was also directly related to pore size because of its fundamental influence on soil moisture tension.

The importance of pore size in establishing a frost susceptibility criterion was also recognized by Townsend and Csathy (1936b). They sought a simple means of establishing the variation of pore sizes throughout a soil medium. They reasoned that if a pore size distribution could be conveniently obtained for a given soil then it could be correlated against known field performances obtained from a number of sites in Ontario, thereby establishing a criterion for frost susceptibility. Capillary rise tests were performed on samples in the laboratory and the degree of saturation was measured in increments along the length of the wetted specimen. By means of the relationship between pore size and height of capillary rise, they obtained a relation between the degree of saturation (or its complement, the percentage of pores filled with water) and an equivalent pore size corresponding to a given rise above the datum. In this way, the graduation of pore sizes was at least approximately obtained (see Figure 1). The method described is straightforward and only involves a few simplifying assumptions in its theoretical derivation. A problem in using the method would be variation in density of the test specimens, since the pore size distribution of a given soil will depend on its relative density. A requirement for successful application of the method proposed by Townsend and Csathy would therefore be the duplication of the appropriate in-situ density in the laboratory test.

From a correlation with field records at various sites in Ontario, Townsend and Csathy established that the ratio of pore diameter larger than 90 percent of the pores (P_{90}) to the pore diameter larger than 70 percent of the pores (P_{70}), i.e.,

$$P_u = P_{90}/P_{70} \qquad (1)$$

could be used to establish a tentative criterion. Based on the field evidence available to them, they found that for frost susceptible soils the ratio P_u was less than 6, while non-frost susceptible soils had a P_u greater than 6.

Soil samples were obtained from areas where highway pavements had experienced varying amounts of frost damage, ranging from no damage to severe damage. After making due allowance for the proximity of the water table, the field frost susceptibilities of the soils within the depth of frost penetration were estimated. The various criteria were then examined to see if they would have rejected as unsuitable those soils whose field performance indicated detrimental frost effects; on the other hand, where soils had exhibited no detrimental frost action, the various criteria were applied to see if the soils concerned would have been rated as acceptable.

Most of the frost susceptibility criteria based on grain size considerations were effective in rejecting unsuitable soils, with rejections ranging between 84 and 90 percent of frost affected soils based on the method of rating used by Townsend and Csathy. On the other hand, these criteria proved severe in accepting soils which had proven to be non-frost susceptible under field conditions. Using the same rating method, only between 6 and 20 percent of these soils would have been accepted using these criteria. The rate of acceptance of these soils would possibly have been higher using Beskow's capillarity criteria but Townsend and Csathy considered only grain size distribution aspects in their study.

By comparison, the criterion based on pore size distribution proposed by Townsend and Csathy served to reject 75 percent of the unsuitable soils and would have accepted 79 percent of the suitable soils. The lower rejection factor of this criterion would mean that more frost susceptible soils would actually be used in construction than if the other criteria were employed and to this extent, some further modifications would appear warranted. On the other hand, the great superiority of the pore size distribution criterion in accepting for construction "borderline" soils which did not display detrimental frost effects in-situ suggests that considerable savings could be achieved by the use of this criterion.

In a study of the frost susceptibility of some Arctic soils from Lake Hazen, Ellesmere Island, Windisch (1963) found a relationship between rate of capillary rise in dry specimens, about 7 cm. in height, and frost susceptibility, as determined by the frost action displayed by soil samples when frozen in the laboratory. Six samples with grain size distribution curves as shown on Figure 2, were subjected to controlled freezing tests with temperature gradients ranging generally between 0.5 and 0.8°C per cm. The soils with the largest amount of fines displayed the greatest amount of ice lensing, for the relatively large thermal gradients employed. At the same time, the rate of wetting for these soils was lowest - the slope of the height of capillary rise in cm. vs square root of time in minutes is noted for each sample on Figure 2. Windisch noted a good correlation between degree of ice lensing in the samples tested and the slope of the wetting rate curves, as noted in Table 1. Further research is required to expand this criterion to the coarser soils because the wetting rate will obviously reach a maximum in the silt size range and then decrease in the coarser grain size range. The method does present a rapid and simple means of establishing a criterion which is based on pore size. A typical value of the pore size ratio, Pu, of 1.5 was obtained for this arctic silt at a dry density of 77.0 pounds per cubic foot.

FROST HEAVING PRESSURES

When an advancing ice front enters a pore space, it will have a curved surface, the radius of which will be related to the size of the pore (see Figure 3). The same ice front will have areas of opposite curvature adjacent to particles. The radius of curvature in this case will reflect both the size of the particle and the thickness of the double layer; for the case of silt where the thickness of the bound water is small compared to the size of the particle, the radius of curvature will nearly equal the particle radius. Penner (1959) has shown that the following equation is applicable in a freezing soil system to specify freezing temperature change caused by curvature of the ice front:

$$\Delta T = -\frac{2\sigma T}{\rho_i L r} \tag{2}$$

where ΔT = freezing point depression (for the case of curvature associated with advance into a pore space)

σ = ice-water interfacial energy

T = absolute freezing temperature

ρ_i = density of ice

L = latent heat of fusion

r = radius of curved surface

Denoting the pore radius by r_v and the equivalent particle radius by r_p, Yong (1966) pointed out that there was both a temperature depression in a void space of

$$\Delta T = -\frac{2\sigma T}{\rho_i L r_v} \tag{3}$$

and a temperature elevation at the point of reversed curvature about the adjacent particle of

$$\Delta T = \frac{2\sigma T}{\rho_i L r_p} \tag{4}$$

Combining equations 3 and 4 gives the net ΔT in the local region containing a particle and a void space

$$\Delta T = -\frac{2\sigma T}{\rho_i L} \quad [\frac{1}{r_p} + \frac{1}{r_v}] \tag{5}$$

Use of equation 5 requires a knowledge of both the equivalent particle size and the size of a related pore space, which is obviously dependent on the structure or configuration of the soil particles comprising the matrix. For the simple case of uniform particles in a cubic array, it can be shown that r_p and r_v are related by

$$r_v = r_p \left[\frac{n}{1-n}\right]^{1/3} \tag{6}$$

where n = porosity.

The effect on the freezing point of pressure applied at the ice-water interface can be calculated by the Clapeyron equation. The equation in the form written by Penner (1959) is

$$\Delta P = \frac{L \Delta T}{T(V_w - V_i)} \tag{7}$$

where ΔP = change in pressure between ice and water

V_w = specific volume of water

V_i = specific volume of ice

= $1/\rho_i$

The appropriate value of ΔT to substitute in equation 7 can be obtained from equation 5. The value of ΔP so obtained is the measure of required pressure change to alter the freezing point by the same amount as the net change due to curvature. When ΔP is realized in a freezing soil-ice-water system, equilibrium is achieved and the growth of ice lenses is halted. Equation 7 therefore defines the heaving pressure.

The pressure at the ice-water interface can be changed either by changing the pressure in the pore water (the soil suction) or the pressure applied to the ice. In the latter case, the application of external pressure must be to the soil matrix and transfer of stress to the ice must occur at contacts between the ice and the particles, occurring through the bound water layers where necessary. A correction must therefore be made to the heaving pressure manifested at the actual points of contact between ice and particles to relate it to average pressure across the entire surface of the soil matrix. This can be achieved approximately by multiplying the cross-sectional area by the factor $(1 - n)^{2/3}$.

A series of freezing tests were recently performed at McGill University by McKyes (1965, 1966) in which frost heaving pressures were measured in a uniform silt (55 percent by weight of all particle sizes were within the narrow range of 0.01 to 0.02 mm). The measured and predicted values of heaving pressures agreed exactly for this uniform soil - see Figure 4. McKyes also sought a correlation with data on heaving pressures obtained by other researchers (Penner (1959), Hoekstra et al (1965)). Well graded soils had been used in these other experiments and so it was necessary to take an equivalent particle size for use in equation 5. McKyes found that the best fit of the data was obtained by using the particle size of which 10 percent of the sample is finer (the 10 percent passing size). As can be seen from Figure 4, good agreement with the theory is obtained with this equivalent particle size.

The silt used by McKyes had been used for an extensive series of soil suction measurements by Chahal and Yong (1965). By using the relation between size of pore and soil suction necessary to remove water from a pore of such size, Yong (1966) determined a relationship between the effective pore size for the silt found from the frost heaving experiment and the moisture tension. From the moisture tension-saturation data available for this silt, it was observed that the moisture tension associated with the effective pore size was that obtained at 70 percent saturation in the silt (at room temperature). Yong (1966) then checked the relationship between heaving pressures and moisture tension at 70 percent saturation. The results, plotted on Figure 5, show excellent agreement between theoretical and experimental values.

The demonstrated relationship between particle and pore sizes and heaving pressures suggest an interesting relationship between frost susceptibility criteria and depth of frost penetration (which can be shown to be related to the Freezing Index at a particular locality). Consider a well-graded soil with 3 percent finer than 0.02 mm, i.e., a soil classified as just on the borderline of frost susceptibility. The 10 percent passing size would be around 0.04 to 0.05 mm. From equations 5, 6 and 7, a heaving pressure of 2.5 to 3.0 psi was calculated (McKyes, 1966). This corresponds to an overburden pressure of about 3.5 feet. In other words, if the frost penetration in an area were equal to 3.5 feet, the overburden pressure at the freezing front in this particular soil would be sufficient to prevent ice segregation. Since many of Casagrande's field observations were made in New Hampshire, where a frost penetration of about 3 feet is probably representative of average conditions, the correlation between effective grain size and heaving pressure is striking.

However, in more northern latitudes, where frost penetrations of 5 to 7 feet are common, the frost heaving theory predicts that a soil could have a larger quantity of fines, since the resulting larger heaving pressure would be counteracted by the greater overburden pressure above the frost front. It is important to note in this connection that Townsend and Csathy (1963b) found a rather low acceptance factor for the Casagrande criterion when applied to soils in-situ in Ontario. The above considerations would suggest that a higher quantity of fines would be acceptable under typical winter conditions in Ontario, and this is supported by field experience.

PROPERTIES OF FROZEN SOILS

The shear strength of partially frozen soils has been the topic of continuing research at McGill University. The results have been presented in a series of papers by Yong (1963a, 1963b, 1965, 1966). In this paper it is intended to give only a brief resume of this work to illustrate the "state-of-the-art" of this growing branch of Frozen Soil Mechanics.

Due to matric and osmotic potentials in the pore water, all of the water in a soil (saturated or unsaturated) does not freeze at $0^{\circ}C$. A relation exists between the moisture potential and the freezing temperature of water; as the moisture potential approaches zero (bulk water) the freezing temperature is unaffected while at high values of moisture potential (characteristic of clays) freezing is not complete at $-20^{\circ}C$. Therefore, frozen soils, so-called, often have both ice and water present and are more correctly termed "partially frozen soils".

The measurement of soil suction is now a common laboratory procedure and can be achieved by several techniques. The soil suction or moisture potential in unfrozen soils varies with water content or degree of saturation, being a maximum at low water contents or saturations and a minimum at high water contents or saturation. When soil is completely saturated, the soil suction is largely a measure of osmotic potential and so values of soil suction in saturated silts and sands are near zero. Decreasing the degree of saturation means that curved meniscii are established in smaller and smaller pores and so the matric potential increases with decreasing saturation for any soil. It has been established that there is a relationship between moisture potential and the unfrozen water content (determined by a calorimetric method) of a given soil at various test temperatures (see Figure 6). The correlation shown is with soil suctions associated with the original unfrozen water content of the soil, as determined at room temperatures. Since some of the factors which contribute to the moisture potential in a soil are temperature dependent, the moisture potential will be subject to variation with temperature (Williams, 1963). However, such variations should not be great in soils of relatively low osmotic potential (such as the silts and clays of low activity tested so far at McGill) and so the correlations made to date with moisture potentials measured at room temperatures appear satisfactory.

The investigations of the shear strength of frozen soils have so far been concerned with rapid shear tests. A direct shear apparatus was employed and failure of the soil occurred within five minutes of the commencement of shear. Shear strengths were obtained at freezing temperatures ranging to -20°C for a silt and a clay, the properties of which are given in Table 2. Since a relation exists between shear strength and water content for unfrozen soils (at least for similar structures and stress histories), the shear strengths measured on the partially frozen soils were plotted against initial water content. Despite some scatter, a reasonable trend was observed for the silt while the results from the tests on the clay displayed no trend at all. The shear strength values were then plotted against ice content, defined as the initial water content minus the unfrozen water content. For the silt, plotting shear strength against ice content had very little effect; the scatter was reduced to some extent. This is because the ice content nearly equaled the initial water content in the silt samples, due to the coarse nature of the silt tested. It does not follow that this agreement with either initial water content or ice content will hold for finer silts, when the results of the tests on the clay samples are considered. For the clay, plotting the shear strength values against ice contents produced a good correlation (see Figure 7).

When the long-term shear strength of frozen soils is considered, considerable complications arise due to the creep characteristics of ice. An investigation of the stress-strain-time relationships of partially frozen soils is currently under way at McGill University. After a series of unsuccessful attempts with axially loaded cylindrical samples, a test apparatus has been devised in which hollow, cylindrical samples are being subjected to torsion. Typical strain-time curves have been obtained from pilot tests on a saturated kaolin clay and are shown on Figure 8. The specimens tested had outside and inside diameters of 1.25 and 0.875 inches respectively and the sample height was 2.8 inches. Despite a large difference in initial water content of 67.0 and 52.8 percent, at the test temperature of -4^{o}C the unfrozen water contents were similar, being 33.3 and 32.4 respectively. From soil suction measurements on saturated kaolin (Woo, 1966), values of moisture potential of 190 and 720 cms of water were inferred at initial water contents of 67.0 and 52.8 percent respectively. The correlation between soil suction and unfrozen water content displays a similar trend to the data plotted on Figure 6, which was obtained on another type of clay. Differences in the degree of ice lens formation were noted in the samples and the investigation will attempt to relate this difference to the varying stress level in the samples, although unavoidable inhomogeneity of the specimens will complicate this task. The creep characteristics of the frozen soils will be compared with the results of other current investigations of creep (Chen, 1965).

CONCLUSIONS

Recent studies of frost susceptibility criteria have pointed out the funadmental importance of pore size in the frost heaving mechanism. The fact that the magnitude of the heaving pressure is also a function of pore size suggests that the criteria for frost susceptibility will be influenced by the local depth of frost penetration, since this will influence the overburden pressure at the freezing front. This means that a greater quantity of fines can be permitted in the more northern locations for a given degree of ice segregation.

The shear strength of frozen soils can be related to the ice content of the soils, which in turn is a function of the soil suction or moisture potential in the pore water. Investigations of the stress-strain-time relations for frozen soils are progressing.

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TABLE 1

COMPARISON OF SLOPES OF WETTING CURVES AND DEGREE OF ICE LENS FORMATION - LAKE HAZEN SOILS

	Sample					
	1	2	3	4	5	6
% finer than 0.02 mm	15	23	19	45	70	72
Average slope, h vs $\sqrt{t}$ (two tests)	1.24	0.97	0.53	0.28	0.24	0.26
Ice lensing value (see note 1)	2	3	6	14	16	15
Predicted ice lensing value (see note 2)	3	4	7.4	13.9	16	14.6

Notes:

1. Ice lensing value is the summation over 6 separate freezing tests on each sample of the following arbitrary values:

   value = 1; single ice lens formed
   value = 2; small group of thin ice lenses
   value = 3; many and/or thick ice lenses

2. Predicted values based on slopes of h vs $\sqrt{t}$ curves, using sample 5 as the basis of comparison.

TABLE 2

PROPERTIES OF SOILS USED FOR MEASUREMENTS OF FROZEN SHEAR STRENGTH

		Medium Clay	Silt
Liquid Limit		67.0	25.1
Plastic Limit		28.8	17.0
Specific Gravity		2.73	2.68
Grain Size (by weight)			
% finer	0.15 mm	100	100
	0.10 mm	100	93
	0.05 mm	91	83
	0.01 mm	72	22
	0.005 mm	66	2
	0.002 mm	30	0
	0.0008 mm	0	0

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LIST OF FIGURE CAPTIONS

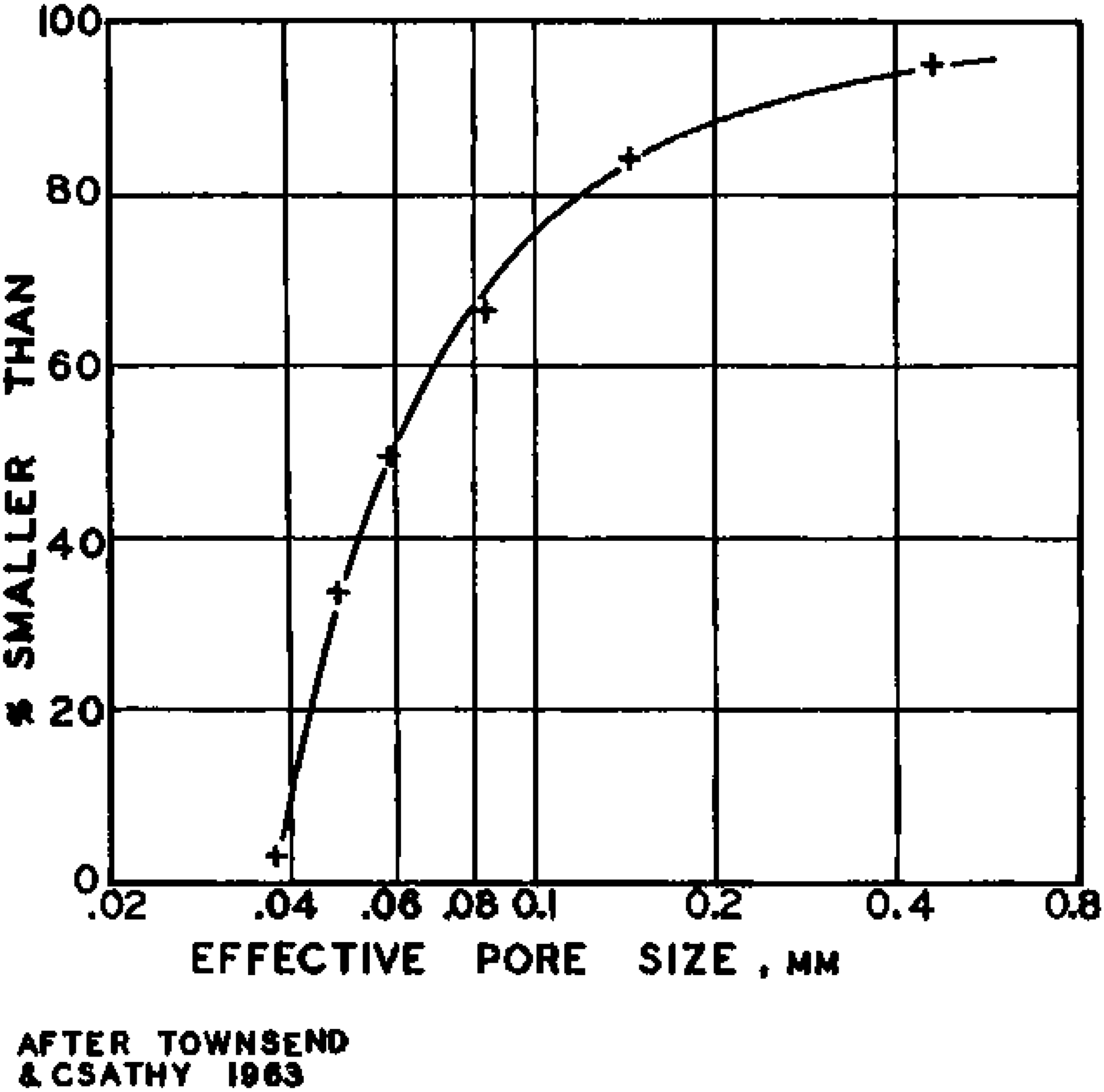
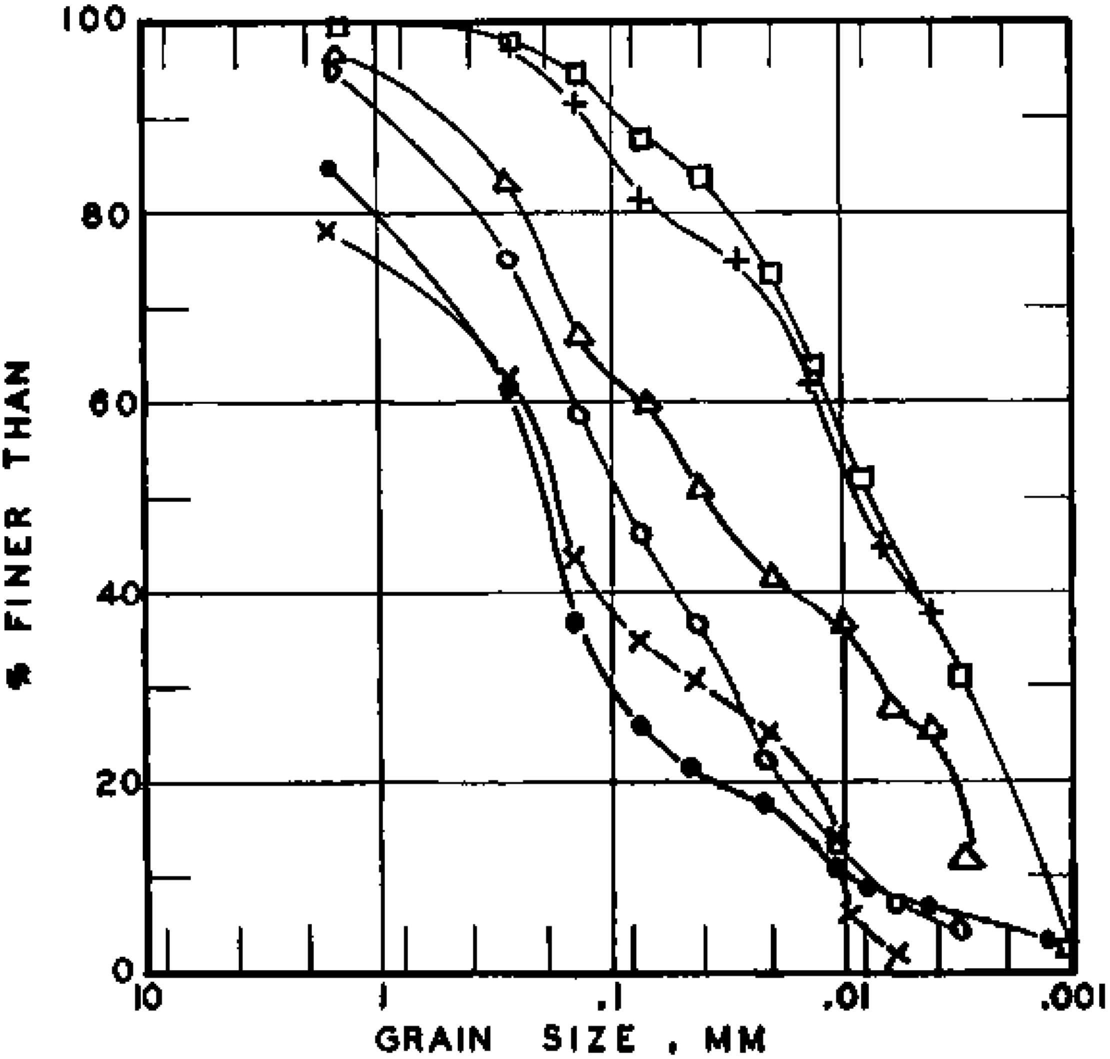

100
80
60
40
20
0
% SMALLER THAN
.02
.04
.06
.08
0.1
0.2
0.4
0.8
EFFECTIVE PORE SIZE, MM
AFTER TOWNSEND
& CSATHY 1963

FIGURE 1



SAMPLE NO.	SYMBOL	SLOPE: H VS $\sqrt{T}$
1	●	1.24
2	×	0.97
3	○	0.53
4	△	0.28
5	+	0.24
6	□	0.26

FIGURE 2

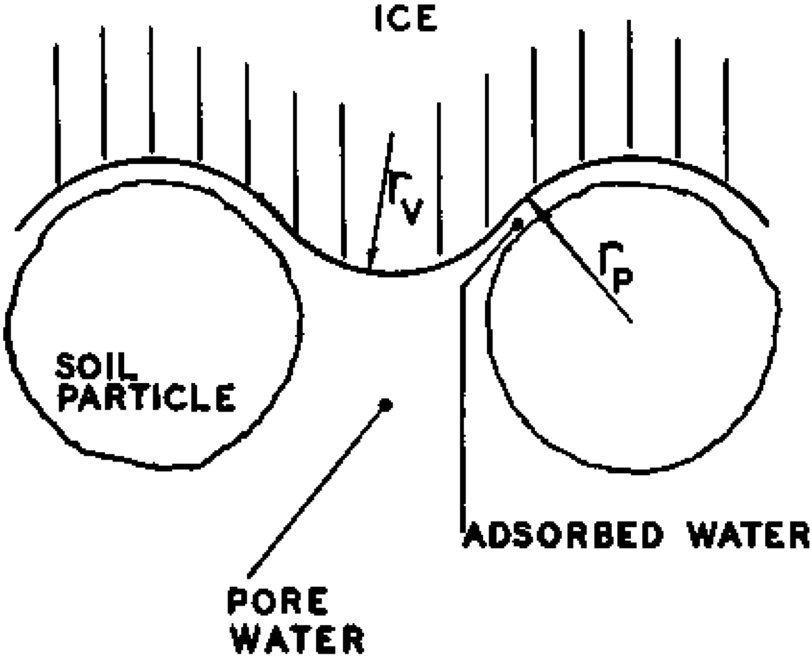
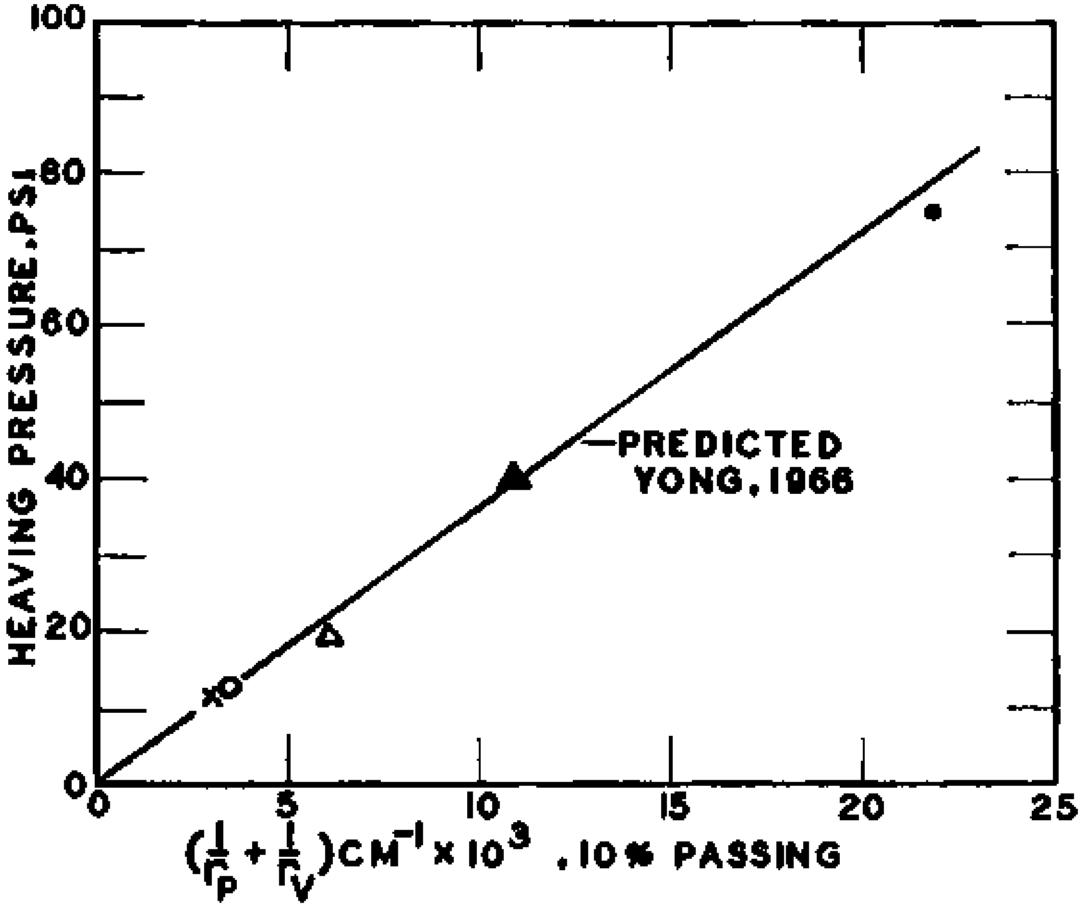


FIGURE 3



EXPERIMENTAL RESULTS

× AUGREY SAND—HOEKSTRA ET AL, 1965

▲ N.H. SILT "

● RICHFIELD SILT "

○ INORGANIC SILT—MCKYES, 1966

△ POTTERS FLINT—PENNER, 1959

FIGURE 4

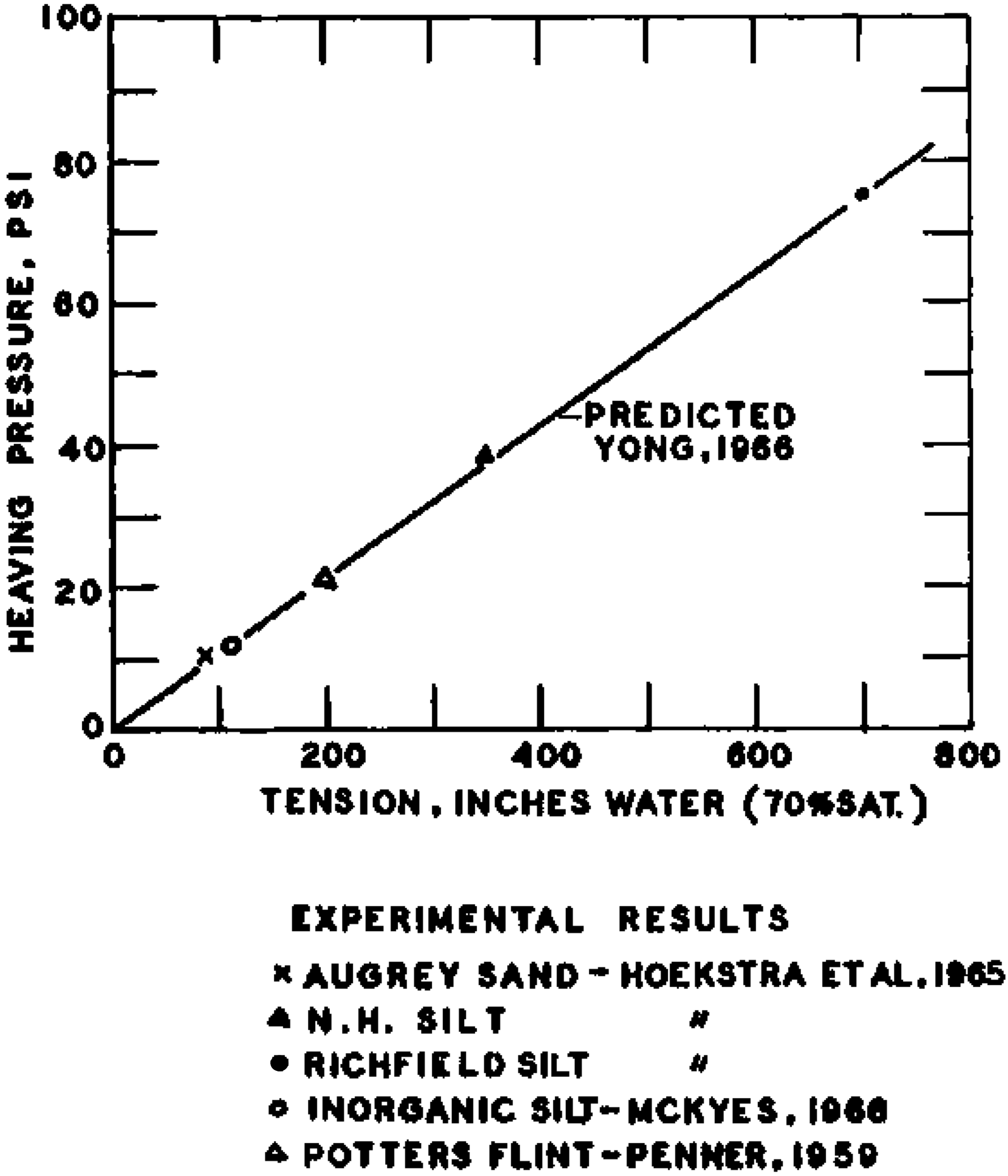
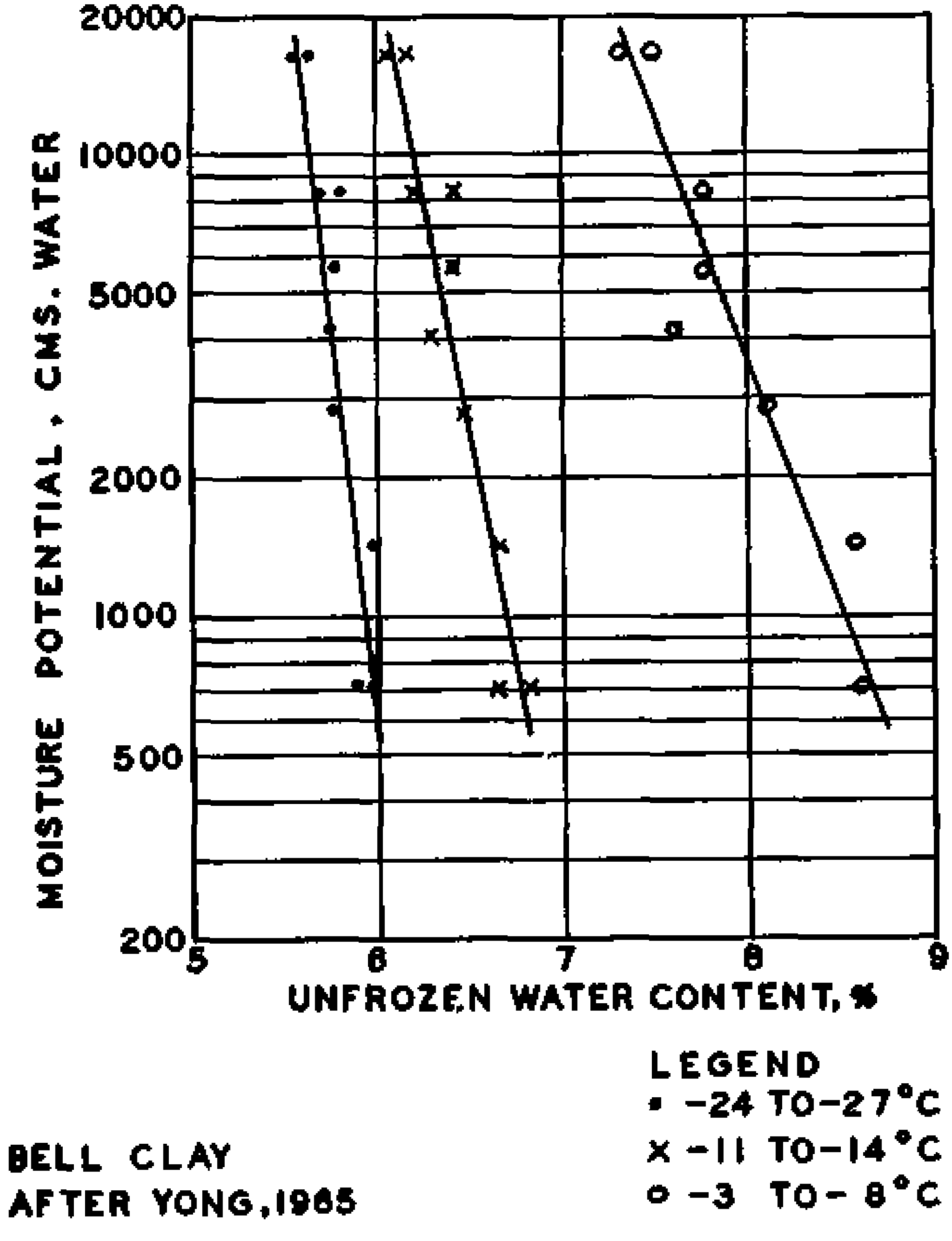
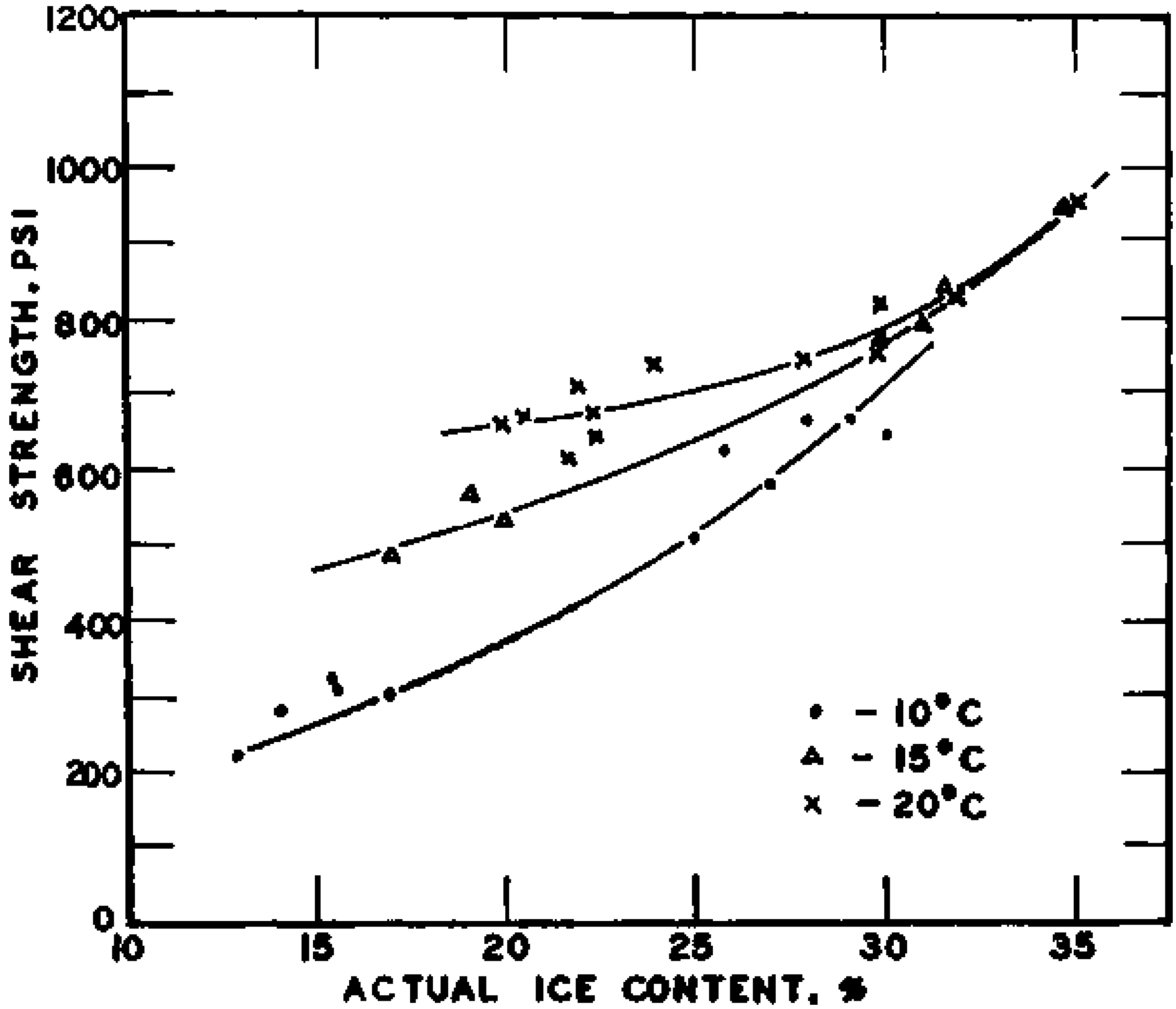

100
80
60
40
20
0
HEAVING PRESSURE, PSI
0
200
400
600
800
TENSION, INCHES WATER (70%SAT.)
PREDICTED YONG, 1966
EXPERIMENTAL RESULTS
× AUGREY SAND – HOEKSTRA ET AL. 1965
▲ N.H. SILT "
● RICHFIELD SILT "
○ INORGANIC SILT – MCKYES, 1966
△ POTTERS FLINT – PENNER, 1959

FIGURE 5



20000
10000
5000
2000
1000
500
200
5
6
7
8
9
MOISTURE POTENTIAL, CMS. WATER
UNFROZEN WATER CONTENT, %
LEGEND
• −24 TO−27°C
× −11 TO−14°C
o −3 TO− 8°C
BELL CLAY
AFTER YONG, 1965

FIGURE 6



AFTER YONG, 1966

FIGURE 7

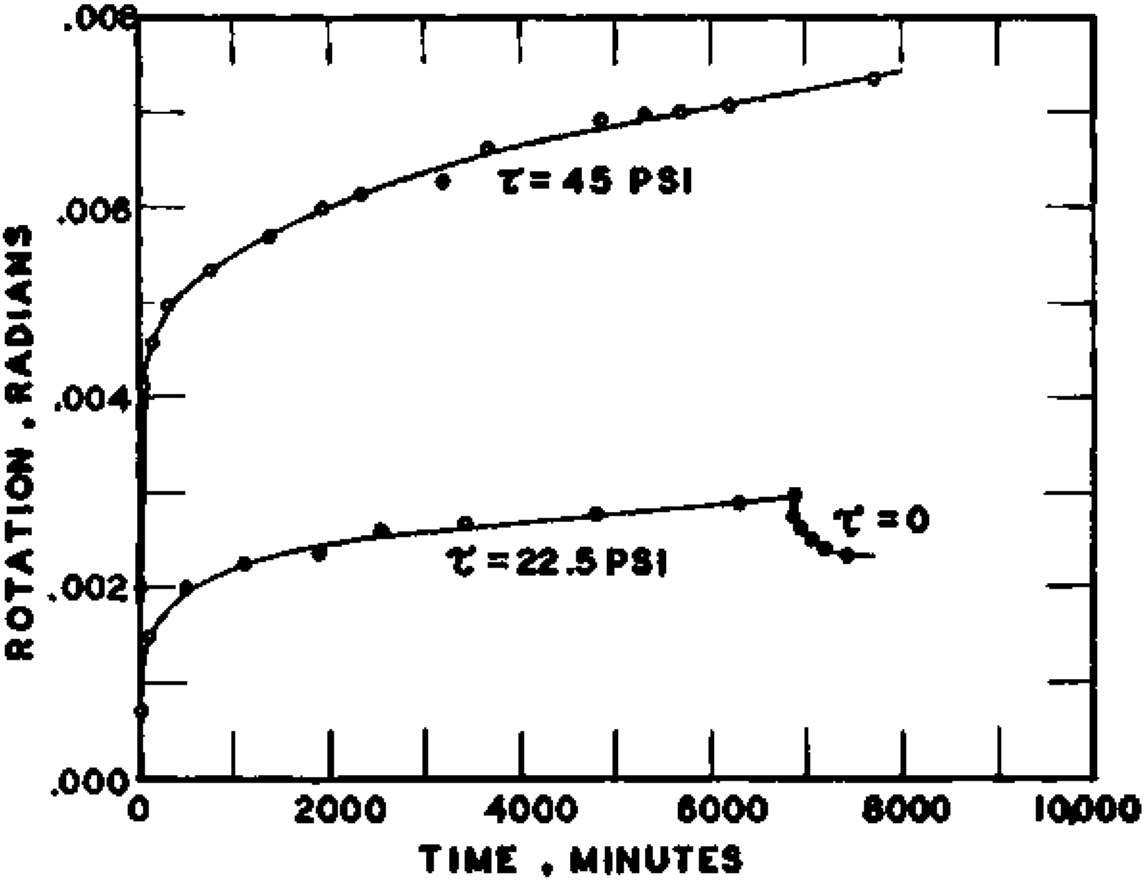

.008
.006
.004
.002
.000
ROTATION , RADIANS
0
2000
4000
6000
8000
10,000
TIME , MINUTES
τ = 45 PSI
τ = 22.5 PSI
τ = 0

FIGURE 8