USE OF THE ICE-WATER SURFACE TENSION CONCEPT IN ENGINEERING PRACTICE

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Many authors use surface tension phenomena to explain relationships among soil type, pressures developed during freezing, and freezing temperature. These relationships are ascribed to effects arising from the situation of the ice and water interfaces within soil pores. Two particular applications are (a) prediction of pressures (or "suctions") developed at the frost line and, thus, the susceptibility of a soil to frost heave, and (b) prediction of the proportions of ice and water as a function of soil type and temperature and, thus, of the thermal properties of the soil. Recently developed soil-testing techniques for these purposes are described. Theoretical and experimental studies indicate these tests to be the basis of improved practical procedures, and the manner of their utilization is discussed. The role of surface-tension concepts in providing a relatively simple picture of many aspects of frozen soil behavior can be compared to the importance of capillarity and surface tension in understanding the behavior of unfrozen soils.

• THERE are two aspects of soil freezing that have been the subject of theoretical and experimental studies of practical significance: (a) prediction of the susceptibility of soils to frost heave, and (b) prediction of the phase composition (proportions of ice and water) and hence thermal properties of frozen soils. Both aspects involve consideration of surface tension phenomena; however, the practical applications do not require detailed understanding of the phenomena. The prediction procedures have only recently been developed, however, and before they are likely to be widely accepted, both engineer and scientist must be satisfied as to the validity of their theoretical background. This will be briefly described in order to show how the procedures advocated are arrived at. Also, the extent to which the procedures have been, or could be, sucessfully employed in field situations is reviewed.

SUSCEPTIBILITY OF SOILS TO FROST HEAVE

There are several procedures for predicting the susceptibility of soils to heave, which have had considerable economic importance (1). Grain size criteria are the most widely used. However, most highway engineers are aware that failures (when the soil does not act as predicted) are not uncommon; there is also a general suspicion that materials are frequently rejected as fill although they would in fact not be susceptible to heaving if utilized under appropriate conditions.

Let us review some fundamental points:

1. Frost heave involves the increase in moisture content at freezing, which results from a movement of water to the freezing layer.
2. The movement of water results (for all practical purposes) from a hydraulic pressure gradient in the water.
3. Such a hydraulic gradient must involve the development of a lower water pressure at the frost line than otherwise exists in the water in the underlying soil.
4. If the occurrence and magnitude of such pressure drops at a frost line are predictable, it is but a short step to predicting whether frost heave will occur.

Laboratory Measurement of Suction Developed at Freezing

Laboratory measurement of the pore water pressure at a penetrating frost line is, in principle, simple. A soil sample is placed on a saturated porous filter that is connected to a pore water pressure measuring device; the sample is frozen, starting at the top. One such apparatus (2) also included provision for raising the confining pressure (σ_3) and for initially applying an equal "back" pressure to the pore water. When the frost line is immediately above the porous filter, the observed water pressure must be exactly the same as it is at the frost line. In practice, the apparatus was somewhat complicated, particularly the arrangements for freezing and for the precise measurement of the water pressures and for avoiding stresses due to lateral containment of the sample. Setting up the apparatus for each test was time-consuming, and repetitive freezing of the same sample was difficult. Recently, by using controlled thermoelectric cooling (3) and a transducer to measure the pore water pressure, a new version has been used that allows a test to be completed in about 10 minutes with a reproducibility in successive freezing of 5 to 10 cm of waterhead (0.005 to 0.01 kg/cm^2). This new apparatus (the component parts are now available commercially) enables us to make detailed investigation of factors that may influence the suction developed.

The investigations have shown that the suction (pore pressure drop) for a given soil is always relative to the confining pressure. If a soil under a confining pressure of 1 kg/cm^2 (one atmosphere) shows a suction at the frost line of -0.5 kg/cm^2, at a confining pressure (and initial pore pressure) of 5 kg/cm^2 the pore water pressure (P_w) at the frost line will be 4.5 kg/cm^2. The quantity generally known as the heaving pressure is a confining pressure, and it is also equal to the pressure in the ice in lenses (P_i). In talking therefore of the suction developed at the frost line, we should take care to specify that the relevant quantity is

$$P_i - P_w$$

If we establish the value $P_i - P_w$ for a soil sample, we can immediately define the pore water pressure, P_w, that can occur at the frost line at a specified depth in the ground by giving P_i the value of the overburden pressure at that depth. Frost heaving (i.e., ice accumulation) will occur if this value of P_w is lower than the preexisting pore water pressures (or suctions, if above the water table). In practice, frost susceptibility is best defined in terms of the thickness X_m of the layer (if any) in which ice accumulation can occur. Because overburden pressure ultimately prevents ice accumulation, there is a maximum depth for every soil below which accumulation will not occur.

The criterion for ice accumulation is

$$P_i - P_w > \gamma_s X - (X - Z) \tag{1}$$

where

$\gamma_s X$ = overburden pressure (grams/cm^{-2}), and
Z = depth to water table from ground surface (cm).

At a depth X_m (cm),

$$P_i - P_w = \gamma_s X_m - (X_m - Z) \tag{2}$$

and there will be no ice accumulation at depths greater than this. From Eq. 2

$$X_m = [(P_i - P_w) - Z]/(\gamma_s - 1) \tag{3}$$

If X_m has a negative value, there will be no frost heave. Otherwise, heave will occur if the material in question lies within the depth X_m from the surface. Figure 1 shows the relation of X_m to $P_i - P_w$, γ_s, and Z.

Alternative Test Procedure

Although its use represents the most direct and precise method of investigating the pore pressure effects, the apparatus described is not entirely suitable for practical purposes because of its relatively high expense. However, an examination of theoretical aspects suggests an alternative test procedure based on analogy. According to several studies (4, 5, 6, 7), the pore pressure decrease, or more precisely $P_i - P_w$, follows from the limitation on the size of ice crystals imposed by the soil pores. It has been well known to physical chemists for many years that, for small crystals, there is a difference in pressure between the solid and surrounding melt, which is a function of the crystal size. With some simplification, this can be expressed for ice and water as

$$P_i - P_w = 2\sigma_{iw}/r \tag{4}$$

where

r = effective radius of crystal, $\approx$ radius of pore, and
σ_{iw} = surface tension for ice to water (8), ≈ 30 erg/cm^{-2}.

This equation is analogous to the well-known capillary equation governing the rise of water in capillary tubes:

$$P_a - P_w = 2\sigma_{aw}/r \tag{5}$$

where

P_a = pressure of air,
P_w = pressure of water, and
σ_{aw} = surface tension for water to air, ≈ 72 erg/cm^{-2}.

It is well known that this equation, at least for relatively coarse-pored soils, describes the pressure state of water in wet but unsaturated soils with the air-water interfaces in pores of size r. If a saturated soil is placed on a filter attached to a drainage tube containing water at atmospheric pressure and air pressure is applied progressively to the soil sample, the water is eventually displaced from the soil pores. If appropriate attention is given to preventing the leakage of air directly to the drainage system and to the rate of application of the air pressure, the pressure at which air first spreads through the soil is revealed by observation of the drainage (Fig. 2). A series of experiments (9), using translucent soils and microphotography, showed that at this given air pressure a front of air passed through the sample (Fig. 3), which could be likened to penetration of a frost line. Because the pore water pressure is known to be atmospheric (i.e., zero), the air pressure applied is also equal to $P_a - P_w$. It appears reasonable to assume that the quantity r is the same in Eqs. 4 and 5. Accordingly, if the measured value of $P_a - P_w$, which is known as the air intrusion value, is multiplied by the ratio $\sigma_{iw}/\sigma_{aw} = 0.42$, we derive the value of $P_i - P_w$ for that soil. A series of experiments (2) established the correlation between the two quantities (Fig. 4, 2). A form of the apparatus for measuring air intrusion value has been developed (by Geonor in Norway) commercially (Fig. 5).

Field Testing and Application in Engineering Practice

The foregoing investigations suggest a potentially precise method of assessment of frost susceptibility based on determination of the value $P_i - P_w$. Whether the determination is made directly by using a freezing test or indirectly by using an air intrusion test, the direct relevance of this quantity, the explicit consideration of overburden pressures and groundwater conditions it permits, and its relatively substantial theoretical background are in contrast to the arbitrary nature of conventional tests and criteria.

Tests have been carried out in cooperation with the Ontario Department of Transportation and Communications, which involve the sampling of highway subgrade material. For old roads with widespread frost damage, the calculation of $P_i - P_w$ following air

Figure 1. Thickness of soil layer affected by ice accumulation as a function of depth to water table and bulk density.

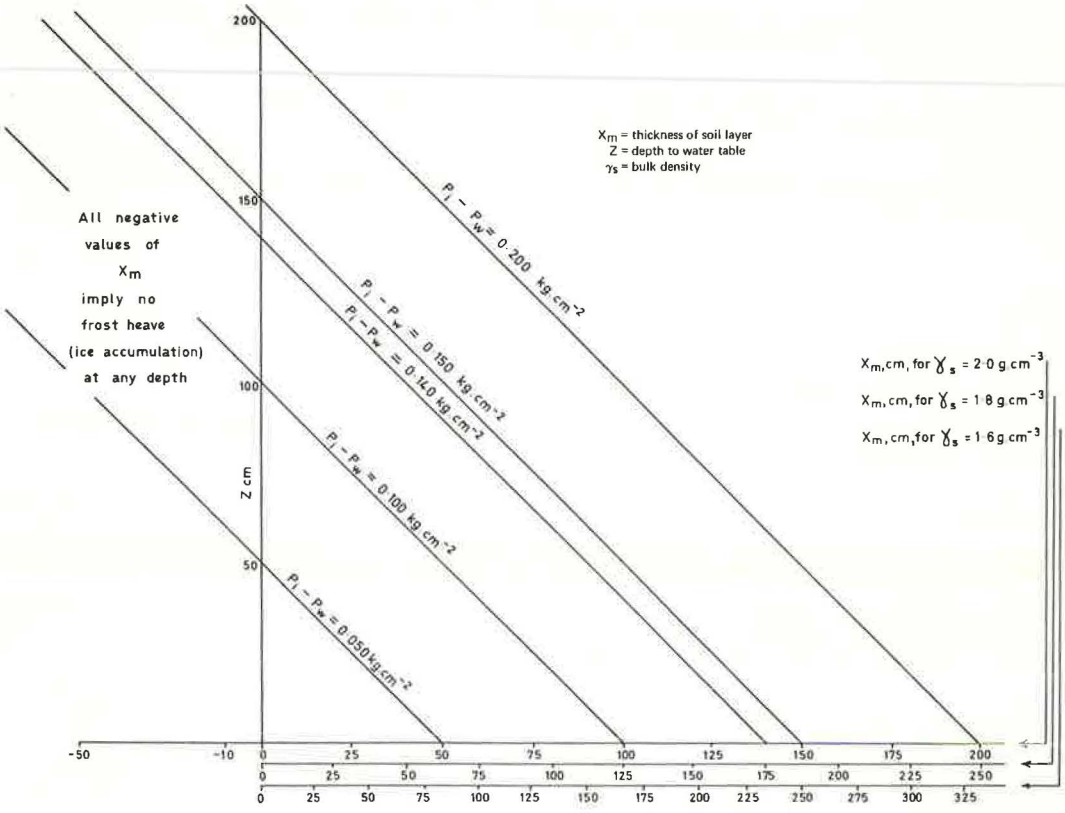


Figure 2. Observations from air intrusion test on highway subgrade material.

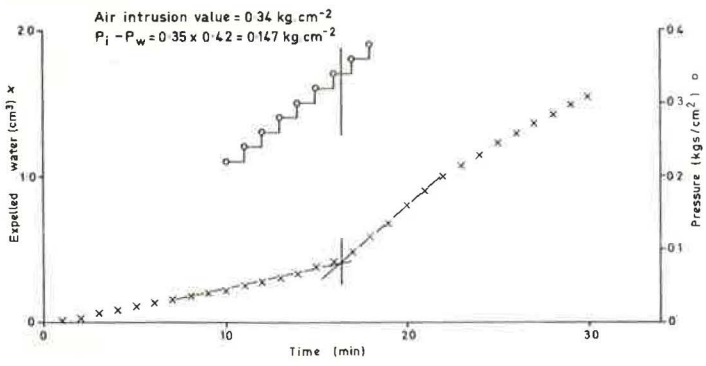


Figure 3. Translucent soil showing advance of air front through pores (light regions) during air intrusion.

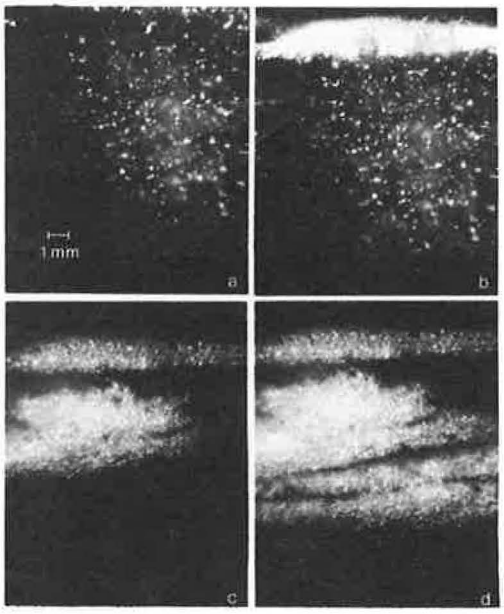


Figure 4. Relation between air intrusion value and pore pressure at a penetrating frost line.

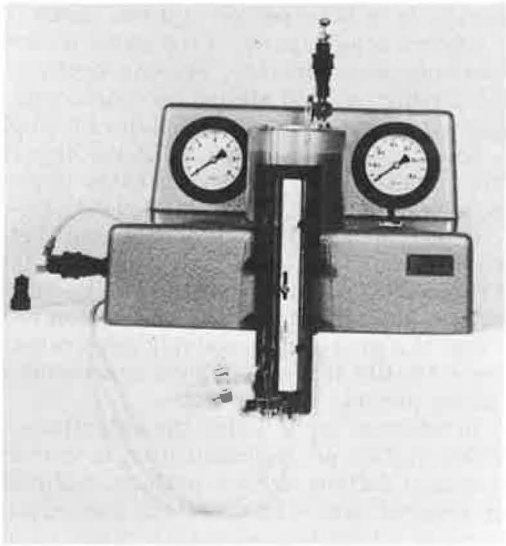
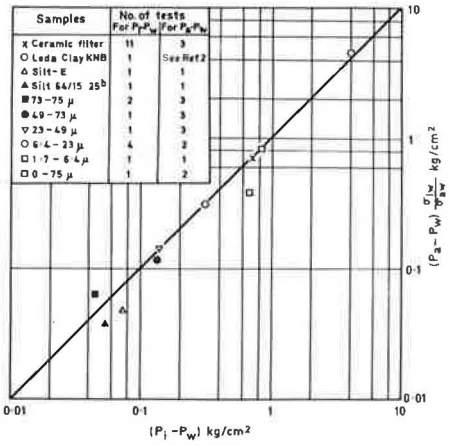


Figure 5. Air intrusion apparatus.



intrusion tests merely confirmed the frost-susceptible nature of the material. A series of tests made on materials that were classified as satisfactory by conventional methods (from a new highway built to the department's current standards but which nevertheless apparently experienced some heaving) is summarized in Table 1. The tests show that heaving is to be expected in three cases (in one case only in very near surface layers). In several other cases, if the depth to water table Z (actually assessed in spring) had been somewhat smaller, heaving would have also been expected. Perhaps, "depth to water table" should always be considered as being closer to the surface than it actually is to allow for wet conditions with incomplete drainage during a freezing period.

Finally, it is of interest that the department's higher classification of ASC (Acceptable Sand Cushion) has been applied to precisely those soils that the present tests also show as having the best (i.e., lowest) P_i - P_w values.

It is recognized by the department that their procedures do not rule out occasional heaving. Such occurrences are often related to particularly wet conditions, and the experienced engineer is usually able to take special measures to prevent, or at least to rectify, the situation. The conclusion to be drawn from the tests summarized, however, is that the procedure involving determination of P_i - P_w leads to predictions of frost susceptibility that are in good agreement with previous experience and that often allow a more precise assessment.

In addition to the latter investigations, air intrusion tests have been applied in the interpretation of ice distribution in various permafrost situations (10, 11, 12). These field applications are not perhaps sufficient to demonstrate the value of the procedures for general use. The questions that remain to be answered are related to technical innovation rather than scientific research and require fairly large-scale tests in association with highway construction. For example, in many cases in engineering practice a limited amount of heave may be tolerated, and the problem of limits for acceptability arises (the procedures only give a yes or no answer). Natural soil materials vary substantially over small distances, and decisions as to frequency of sampling are required. Because the groundwater conditions are explicitly considered in the analysis (common experience has also shown they must be), methods for assessing these are necessary. Groundwater conditions during the winter are a subject that requires much investigation.

In many highway projects, the question arises as to the frost susceptibility of a relatively fine uniform silty-sandy material that may be available in substantial quantity. To regard such soils as unacceptable, if in fact they could be utilized as construction materials under appropriate overburden and groundwater conditions, is a mistake of considerable economic importance. To utilize them and experience subsequent failure are equally serious. It is precisely with marginal soils of this type that the air intrusion test is most easily performed. The time involved per sample compares favorably with that for grain size analysis. The determination of P_i - P_w for "dirty" gravels and other mixed soils can be better determined by using the freezing tests. Perhaps the air intrusion procedure (which is inexpensive and "portable") should be regarded as an on-site test, with occasional samples being tested using the freezing procedure at a central laboratory. Experience to date indicates that, for simplicity and speed of operation and for reproducibility of results, the freezing test is to be favored over the more indirect air intrusion approach.

The answer to these questions will only be obtained from fairly comprehensive trials. At the very least, such trials would give further insight into the problem of frost susceptibility.

PHASE COMPOSITION AND THERMAL PROPERTIES

It has been firmly established in the last 20 years that frozen soils contain both ice and unfrozen water (13, 14, 15). The amount of unfrozen water is a function of temperature and of soil material, and in fine-grained soils it is present in very significant quantities at those temperatures that are of the greatest practical interest (Fig. 6, 15).

Our knowledge of the interrelationship of soil composition, temperature, pressure, and proportions of ice and water present is currently of the greatest importance in making possible the prediction of thermal properties of freezing soils. The latent heat involved in changes in the proportions of ice and water present in the soil in most cases

totally dominates the values now known as the apparent specific heat (15, 16) and the apparent heat capacity of freezing soils (Fig. 7, 16). It is relatively simple to calculate, with a reasonable degree of accuracy, heat capacity and thermal conductivity once the proportions of ice and water, as a function of temperature, are known.

These values may be predicted by using relatively simple and standard laboratory tests, which are carried out at room temperature, that determine the suction-moisture content relationship of the soil. As water is removed from a (unfrozen) soil, the remaining water is under a progressively greater negative pressure or suction (17). This phenomenon, well known to agronomists for many years, is in large measure ascribable (at least for fairly wet soils) to the capillary relationship given above: $P_a - P_w = 2\sigma_{aw}/r$. With the reduction of water content, the interfaces between air and water (menisci) lie in smaller and smaller pores, and accordingly the water shows a greater suction (i.e., $P_a - P_w$). The relationship between suction and moisture content is determined by using "suction plates" or "pressure membrane" apparatus (18). It is important to note that we are not concerned in this case with a specific critical value of $P_a - P_w$ (at which air first enters the soil) but instead with a series of values (Fig. 8, 15) greater than the air intrusion value.

Analogous to this drying process is the freezing of the soil after the initial formation of ice; freezing continues progressively as the temperature falls below 0 C with extension of the already present ice in the soil into smaller and smaller pores. A progressively lower temperature is required for freezing to continue. The temperature (11) is given by

$$\Delta T = 2\sigma_{iw} TV/rL \tag{6}$$

where

ΔT = temperature below 0 C,
T = temperature, deg K,
V = specific volume of water, and
L = latent heat of fusion.

By combining Eqs. 4, 5, and 6, it follows that the water content found with the pressure membrane apparatus at a suction of $P_a - P_w$ is the water content that will occur in the frozen soil at temperature ΔT as given by

$$\Delta T = [(P_a - P_w)(\sigma_{iw}/\sigma_{aw}) TV]/L \tag{7}$$

[The term σ_{iw}/σ_{aw} is modified in certain cases (11, 19).]

The relation has been verified (18) with a high degree of precision over a narrow temperature range (0 to -0.2 C) and with somewhat lower precision to approximately -1.0 C (15) (Fig. 9). Determining the proportions of ice and water by calorimetric or other means is often cumbersome, as also is the direct determination of the thermal properties as a function of temperature. The suction moisture content test that is carried out widely in many agricultural laboratories and that can with equal ease be utilized in geotechnical laboratories appears to be a convenient means of arriving at thermal properties.

Application in Engineering Practice

Sophisticated methods of highway design, especially those involving thermal insulation, and other procedures designed to limit the penetration of frost require precise values for the thermal properties of heat capacity, thermal conductivity, and related functions. General engineering practice where these quantities are required, however, is still to use a somewhat arbitrary assessment based on a comparison of the material in question with materials that have been the subject of experimental measurements of thermal properties. The experimental studies of unfrozen water contents merely point out the inaccuracy of such a procedure, and in time the procedures now advocated may become more widely used.

Figure 6. Amounts of water remaining unfrozen at various negative temperatures.

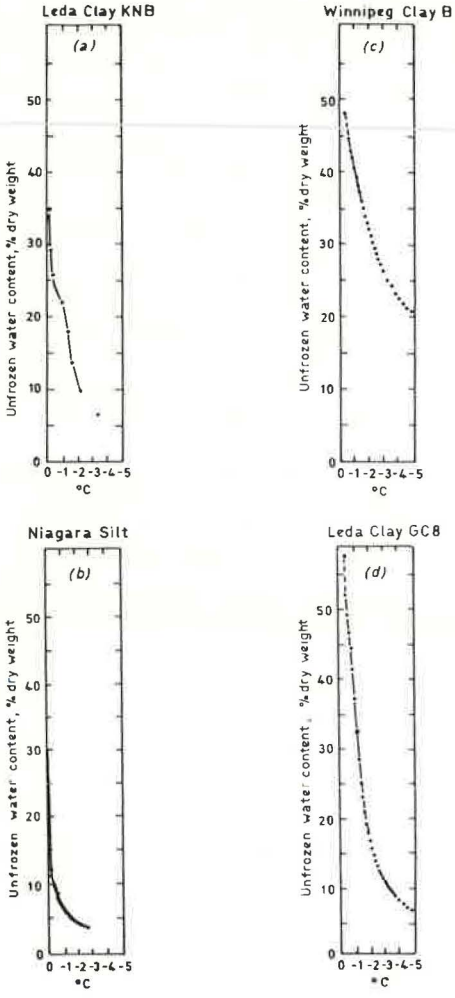


Figure 7. Apparent volumetric heat capacity of frozen soils.

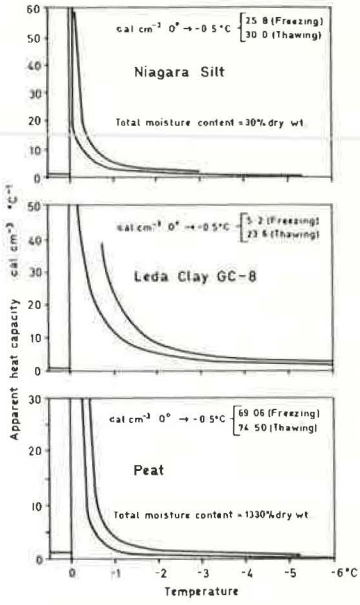


Table 1. Summary of frost damage test results.

Highway 60 Sample Number	Station	Pavement Condition	Observed Depth to Water Table, Z (cm)	Classification[a]	P_i - P_n (grams/cm^{-2})	Depth to Which Heaving Could Occur (X_a, cm)
Location 1a						
LE-78	300 + 00LT	Center-line cracking	86	A	220	134[b]
LE-79	302 + 73RT	Uneven pavement	56	ASC	25	0(-31)
LE-80	305 + 44RT	Center-line cracking	69	ASC	29	0(-40)
LE-81	305 + 44RT	Center-line cracking	69	A	63	0(-6)
LE-82	282 + 70LT	Transverse cracking	71	A	55	0(-16)
LE-83	281 + 05LT	Center-line cracking	76	B	42	0(-34)
LE-84	278 + 55RT	Center-line cracking	69	A	84	15
LE-85	283 + 00RT	Uneven pavement?	76	ASC	16	0(-60)
Location 1b						
LE-75	404 + 40LT	Uneven pavement?	102	NASC	38	0(-64)
LE-76	402 + 50LT	Uneven pavement?	96	A	80	0(-16)
LE-77	404 + 32RT	Uneven pavement?	66	A	147	81[b]
Location 1c						
LE-74	421 + 17LT	Uneven pavement?	104	ASC	21	0(-83)

Note: γ_s assumed to be 2 grams/cm^{-3}.

[a]The department classifies soils for suitability in highway construction on a descending scale: ASC, NASC, and A to E. The classification is not exclusively concerned with frost susceptibility but with overall suitability under normal conditions.

[b]Sample actually taken within this depth.

Figure 8. Suction-moisture content relations of four soils (determined at room temperature).

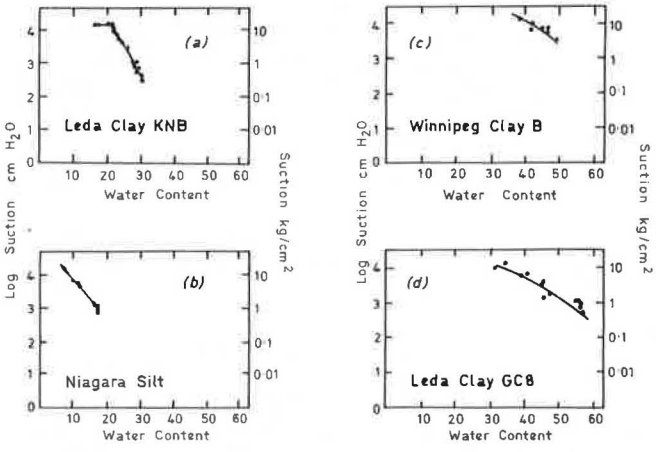
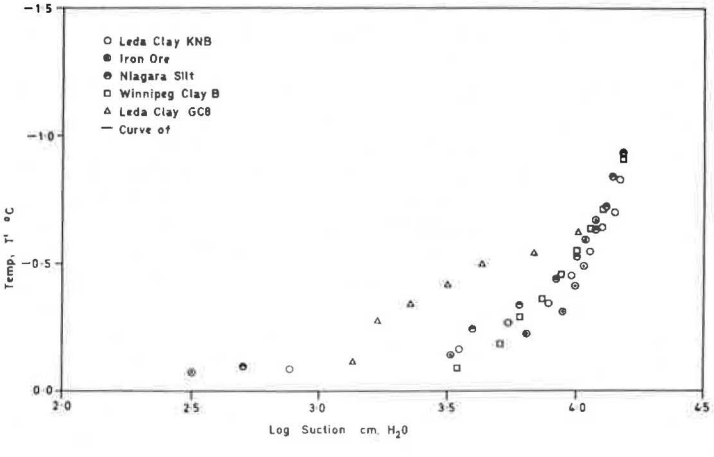


Figure 9. Relation between suction measured in suction-moisture content tests and temperature at which an equal quantity of unfrozen water occurs in the frozen soil.



The use of pressure membrane and suction plate measurements appears justified for predicting thermal properties to -1.5 or -2 C. This covers the range of temperature where unfrozen water content and thermal properties vary most critically. Although capillary theory is scarcely applicable to lower temperatures (there being insufficient water to provide menisci), well-established correlations with other tests involving soil-water free energy (suction) relations (18) give additional significance to these procedures.

BRIDGING THE GAP: THEORY TO PRACTICE

The increased understanding of soil properties deriving from surface tension concepts is also important because of the role such understanding has in the more or less intuitive approach used in much engineering design. It provides a conceptual framework for considering the effects that applied stresses have on the frozen soil system and for understanding the deformation properties of frozen ground as they are known from both laboratory and field experience.

The role of exposure to freezing and thawing in changing the properties of clays is now understood—the suctions developed during freezing are sufficiently great to produce a substantial preconsolidation effect, evident everywhere in the ground surface layers exposed to annual freezing, while the formation of ice lenses leads to numerous discontinuities and a friable soil structure (11). The effects of temperature change, within the frozen state, in producing moisture migrations and other long-term changes in the distribution of ice and water become clearer. The latter are also involved in the phenomenon of long-term creep, and the deformations to be expected in association with load-bearing foundations exposed to temperature change in cold regions over long periods of time.

Very significant contributions have been made, especially in the study of phase composition of frozen soils, by authors who do not support surface tension concepts. In a notable example, Low et al. (20) use relative humidity and thermodynamic functions as the basis for analysis: such an approach, however, demands a specialized understanding that is not required for the more easily grasped physical concepts. The various approaches of different authors are often not contradictory but complementary and reflect the different aims and backgrounds of the agronomist, engineer, and research scientist.

There is such a wide measure of agreement over many of the experimental observations (carried out by different scientists) that, no matter what conceptual pictures we may use to explain the observations, we must conclude that we are dealing with a substantial body of knowledge. The situation is similar to that of the role of capillarity in unfrozen soils; whether we refer to "apparent cohesion," negative pore pressures and effective stress, or relative free energy, there is no doubt that the engineering procedures involved in working with unsaturated soils have been greatly aided by the application of quite elementary concepts of capillarity and surface tension. This progress has occurred in spite of the fact that some soil physicists and other scientists may still be discussing at length the exact nature of and behavior associated with surface tension forces. The potential benefits in the field of frozen-ground engineering from the studies described in this paper may be similar.

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