Soil Suction Effects on Partial Soil Freezing

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The ability of water to move in soils under temperature, concentration, pressure or other gradients, is dependent to a great extent on the particle interaction characteristics of the soil-water system. In both saturated and unsaturated soils, the total effect of such interaction may be measured and described in terms of soil suction (pF) or moisture potential. This potential of water can be a convenient tool since it may be used without specifying exactly the nature of the forces holding water to soils.

This paper presents measurements of soil suction and relates them to the partial freezing phenomenon of three soil types—a kaolinitic clay, a medium feldspar quartz clay, and a silt. Over the range of temperatures considered (from 0 C to -16 C), it was shown that the quantity of water remaining unfrozen may be related directly to the soil suction parameter.

The importance of freezing or thawing history may be noted in the difference in quantity or percentage of water remaining unfrozen, depending upon whether the test samples were frozen to the test temperature or thawed to the test temperature from a previous lower temperature. As example, for the medium clay at a pF of 3.11 and at -0.5 C, the unfrozen water content dropped from 38.1 percent for samples frozen to the test temperature, to 21.5 percent for others thawed from a lower temperature to the test temperature of -0.5 C. At -16 C, the drop was from 9.5 to 7.2 percent for the same condition. At a pF of 3.79 and at -16 C, the drop was from 7.4 to 5.4 percent.

The pF parameter and partial soil freezing relationships are shown and discussed for the three soils studied. In all cases, the results show that the higher the pF value (measured at room temperature), the greater is the percentage of water remaining unfrozen at any subfreezing temperature. In terms of surface tension forces and interaction of long- and short-range forces (Gouy forces) a lowering of the temperature would increase the former and decrease the latter.

A simplified pressure-membrane technique for soil suction measurements is presented which would allow for routine soil suction determinations.

IN a given soil-water system, soil moisture movement occurs as a result of a variety of causes, including temperature, concentration, pressure, and other physical and chemical gradients. In both saturated and unsaturated soils, the ability of water to move is to a large extent dependent on the water holding capacity of the soil. The factors which influence the forces holding water to soil are not well known or clearly understood. Low (1) suggests that both movement and equilibrium of water in soil-water systems are affected by soil and clay-water forces. In general, measurements of soil suction expressed in pF units (2) or as moisture potential serve to provide a useful understanding of moisture retention, which in turn gives an indication of the interaction characteristics of the soil-water system. This includes menisci or capillarity effects and interaction of the long- and short-range forces in the system. The moisture potential, or specifically the soil moisture potential may be defined as the energy or amount of work required to move a unit mass of water from a position within a soil mass to a free water surface.

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Since many of the problems arising in the determination of properties and characteristics of soils are in part dependent upon soil moisture relationships, it becomes necessary to investigate soil suction in terms of basic soil parameters. The purpose of this study is to establish these relationships with initial application to the understanding of the role of moisture potential or pF in partial soil freezing. A secondary purpose is the design and development of simplified equipment and techniques which would allow greater flexibility in the measurement of pF in general.

In previous studies on soil freezing (3, 4, 5), it has been established that total freezing of pore water is not often realized. The results show that the quantity of soil-water remaining unfrozen varies with factors such as temperature, soil composition, and initial water content. It is suggested (6, 7, 8) that unfrozen water in partially frozen soils (the term "partially frozen soils" is used to indicate incomplete freezing of the fluid phase) is dependent to a great extent on the interaction characteristics of the particular soil-water system. If one accepts the thesis that the interaction characteristics of a soil-water system are a function of soil composition, configuration, matric potential and interparticle forces (and there is an overwhelming body of studies to indicate that this is so), then it seems reasonable to expect that a measure of this interaction (specifically moisture potential or pF) may be used to describe relationships between original water content and unfrozen water content for any subfreezing temperature. Hence with the indication that forces holding water to soil play a distinct role in the determination of partial soil freezing, then moisture potential or pF measurements could provide a useful understanding of unfrozen water content and subfreezing temperature relationships.

EXPERIMENTAL TECHNIQUES AND PROCEDURES

pF Measurement Techniques

Various methods for soil suction measurement have been and are now in use. Many of these are suitable only for limited pressure or suction ranges and suffer from other limitations and constraints. A detailed evaluation of these techniques has been presented by Croney and Coleman (9) and will not be repeated here. In general the methods and ranges of pF capacity are given in Table 1.

Other methods available for the measurement of soil suction include: (a) continuous flow—variation of suction plate; (b) rapid method—variation of continuous method; (c) pressure plate—another variation of suction plate; (d) oedometer method; (e) vacuum desiccator—similar to balance sorption; and (f) electrical resistance gages.

The method used for this study was based on the pressure-membrane technique since this gives capacities ranging from 0 to at least 6.2 pF units (9). However, instead of a pressure piston arrangement where compressed air is introduced through a point and further actuated by the piston, the device used in this particular study essentially simplifies both pressure application and measurement systems.

Figure 1 is a schematic picture of the experimental technique. Figure 2 shows the details of the sample chamber. The principle of applied pressure as used in this study is more readily explained with the aid of Figure 3. If a soil sample is sufficiently thin to prevent moisture migration due to pressure consolidation, water will leave the sample until the sum of the surface tension forces and forces due to interaction of interparticle forces develop a suction pressure equivalent to the applied pressure. The ceramic filter at the bottom end of the test cell, of high known air entry value, insures the presence of a free water table adjacent to the soil sample. Schofield (2) suggested that the air pressure technique could be used if suitable filters could be provided.

TABLE 1

METHODS AND RANGES OF pF CAPACITY

Method	pF
Tensiometer	0 - 2.9
Direct suction	0 - 3.0
Suction plate	0 - 3.0
Centrifuge	3.0 - 4.5
Sorption balance	5.0 - 7.0
Freezing point depression	3.0 - 4.5
Pressure membrane	0 - 6.2

After placing the test cell with the prepared sample in the pressure-membrane

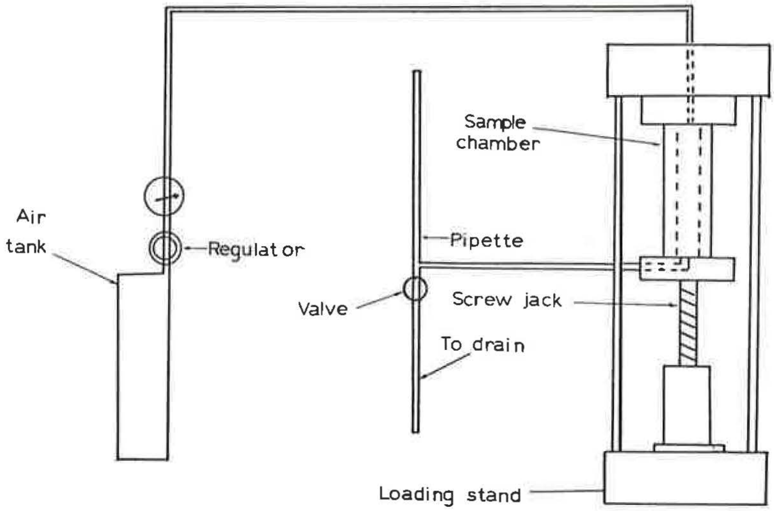

Figure 1. Soil suction apparatus.

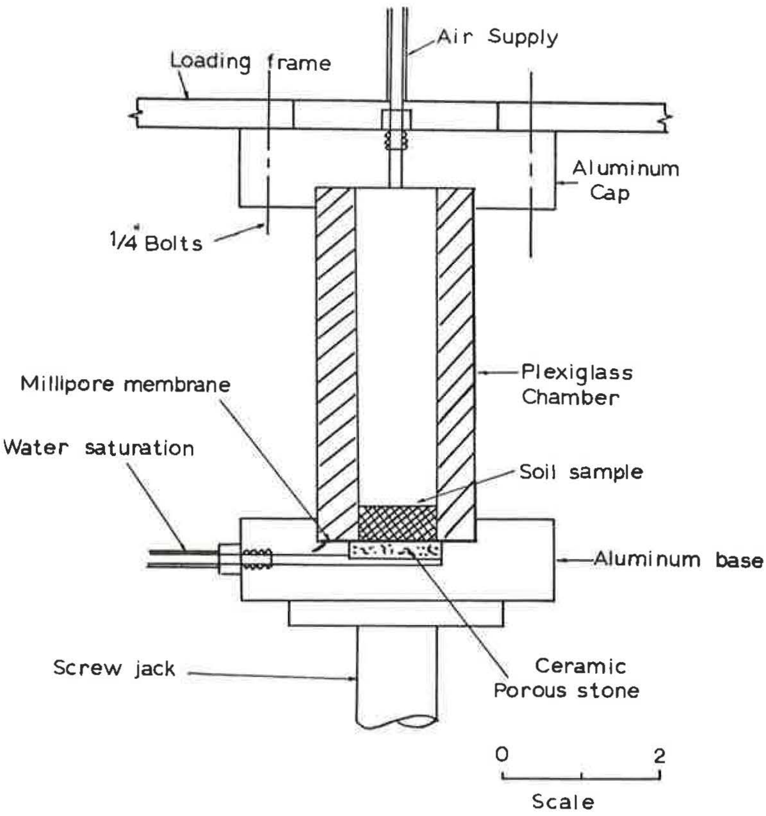

Figure 2. Cross-section of sample chamber.

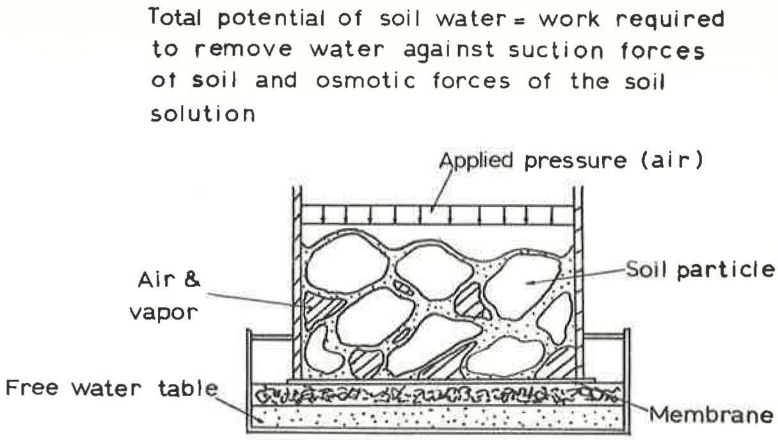

Figure 3. Principle of applied pressure.

TABLE 2

SOIL PROPERTIES AND CHARACTERISTICS

Consistency	Plastic Clay	Medium Clay	Silt
Liquid limit	74	67	25.1
Plastic limit	31	28.8	17.0
Specific gravity	2.75	2.73	2.68
Grain size (by weight), % finer:			
0.15 mm	100	100	100
0.10 mm	100	100	93
0.05 mm	100	91	83
0.01 mm	100	72	22
0.005 mm	100	66	2
0.002 mm	100	30	0
0.0008 mm	80	0	0
0.0005 mm	67	0	0

system, a free standing head of water is introduced on top of the specimen in the cell. The application of air pressure to the water forces water through the soil-water system and with time, equilibrium is reached—signified by no further extrusion of water from the system. The total soil moisture stress is then expressible as the moisture potential or soil suction since the applied air pressure is known and the residual water content can be determined. Since the moisture potential represents the total soil moisture stress of the soil-water system (i.e., the suction or pressure necessary to extract moisture from the soil-water system for a particular configuration), it can readily be seen that it is possible to derive the relationship for moisture potential as a function of water content for a particular soil.

Sample Preparation and Unfrozen Water Content Determination

The soils used were a plastic kaolinite clay, a medium feldspar quartz clay and a clayey silt, the physical properties of which are given in Table 2.

X-ray diffraction analyses showed that the predominant mineral for the silt was quartz with traces of feldspar. In the case of the medium clay, both feldspar and quartz were registered together with trace fractions of chlorite, biotite and amphibole. The plastic kaolinitic clay (Bell clay) was first procured as a kaolin clay. However with subsequent use, it became evident that the expected performance was being obscured. The x-ray diffraction pattern showed the kaolinite peaks but also registered trace fractions of degraded kaolinite, chlorite, flour-apatite and quartz. It would seem that the degraded kaolinite with properties not unlike amorphous materials has subverted to some extent the normal behavior pattern of the kaolinite.

To arrive at varying particle orientation and densities for the determination of percent unfrozen water the test samples were either compacted in a molding cell or consolidated from a slurry. These prepared samples were subsequently wrapped in wax paper following extrusion from the cells and stored in a freezer for a 72-hr period. The frozen samples were not completely saturated, as is evident from the method of sample preparation. This procedure seemed necessary if variations in total moisture stress were desired, consistent with a constant compactive effort. The calorimetric method was used to arrive at the quantity of water remaining unfrozen at the desired test temperature.

RESULTS

Soil Suction

Figures 4 and 5 show the relationship between soil suction and water content at room temperature. Initially, all the soils tested for soil suction were compacted in the molding cell with a spring tamper adjusted to provide approximately 3-psi compactive pressure. Soil suction or moisture potential for samples compacted in this manner are designated as "medium compacted."

Resultant consolidation or compression of the medium compacted samples arising from the air over-pressure in this pressure membrane technique is negligible at low pressures and insignificant at the higher pressures. To provide a better understanding of configuration or particle orientation effects on soil suction, both the kaolinitic clay (Bell clay) and silt soils were also used in initial slurry form, i.e., slurry samples were used for soil suction measurements. Corresponding results for these samples are shown together with the medium compacted samples. In initial slurry form, equilibrium moisture retention under any applied air over-pressure was reached only after some degree of consolidation or compaction had occurred because of the applied pressure.

As expected, silt slurry samples produced lower values for moisture potential at corresponding water contents in comparison with medium compacted samples. The greater degree of scattering for the silt slurry samples would suggest a high random reorientation in resultant compression or consolidation. In the plastic Bell clay, although it may not be immediately evident why the slurry samples have higher moisture potentials or soil suction values at corresponding water contents when compared to the same samples prepared with the spring tamper, the answer may be found in the final reorientated or equilibrium structure of the initial slurry samples. The water holding capacity of clay samples compacted statically (as may be visualized by the air over-pressure) is higher than those compacted with a spring tamper.

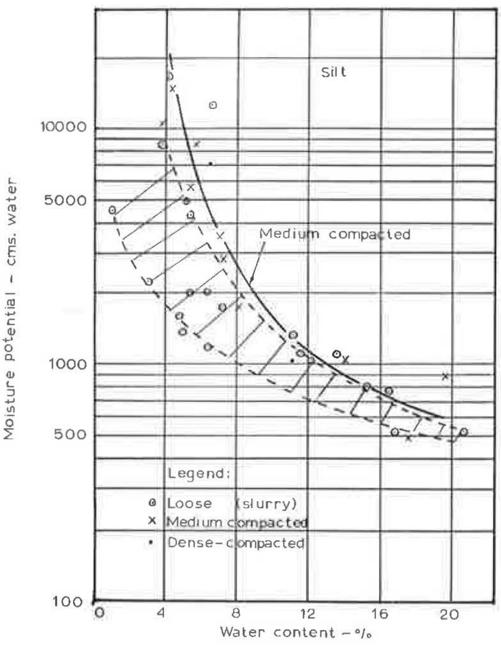

Figure 4. Moisture potential and water content.

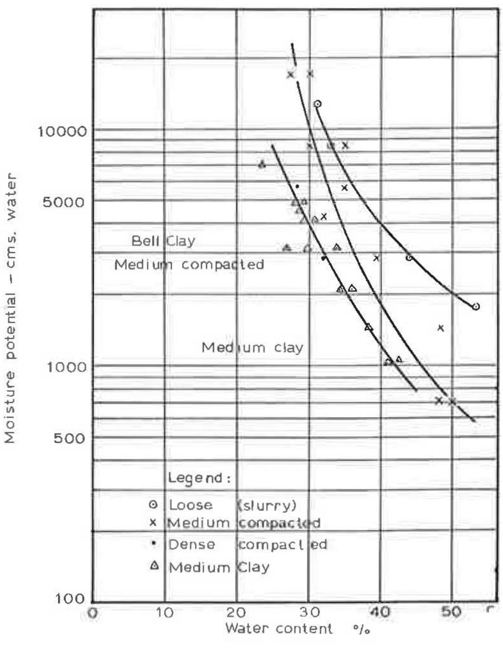

Figure 5. Moisture potential and water content.

As anticipated and indicated in previous research, pF or moisture potential decreases with increasing water content. The relationship is not necessarily linear. On the basis of forces of interaction, it is expected that lower water contents would give rise to a higher interaction characteristic between particles presuming that the degree of saturation is maintained. Again, the interaction characteristics include matric and osmotic potentials. This may be verified by examining the swelling and shrinkage characteristics of such soils.

Proceeding along this line of reasoning, it follows that the ability to freeze soil water must be dependent upon the facility for freezing of water within soil voids wherein interaction occurs. The greater the intensity of interaction, it would necessarily seem that the lower must be the temperature needed to freeze the pore water. Schofield (2) suggests that the free energy difference (measured in terms of pF or as moisture potential) may be related directly to the freezing point depression. To avoid possible confusion, the moisture potential or soil suction referred to in this paper concerns measurements made at room temperature. Moisture potential dependency on subfreezing temperature is recognized and discussed in a later section, however the relationships shown and discussed herein concern themselves solely with moisture potentials at room temperature.

Quantity of Water Remaining Unfrozen

Figures 6 through 9 show the quantity of water remaining unfrozen for the silt and medium clay soils in terms of initial water content, or percent saturation. Unfrozen water content (i. e., ratio of the weight of water remaining unfrozen and the weight of mineral particles expressed as a percentage) has been related to the original water content (Fig. 6). Because of the difficulty in exact duplication of soil samples and configuration before and after freezing, the values plotted showed some scatter which have been encompassed by upper and lower bounds. The bands shown, which encompass the test values derived, also include the effect of freezing or thawing to the test temperature. It is perhaps unfortunate that both scatter and hysteresis tend to overlap here. The upper boundary represents test results obtained for samples frozen to the test temperature as designated, and the lower boundary indicates those results obtained for samples thawed to the same test temperature. It might be argued that the exact positioning of the boundaries is affected by the scatter. However it cannot be denied that the differences in freeze-thaw are sufficiently marked to define cause and effect. What might be agreed upon is that qualitatively these bands are useful to show the freeze-thaw effect, but do not necessarily quantify this effect precisely.

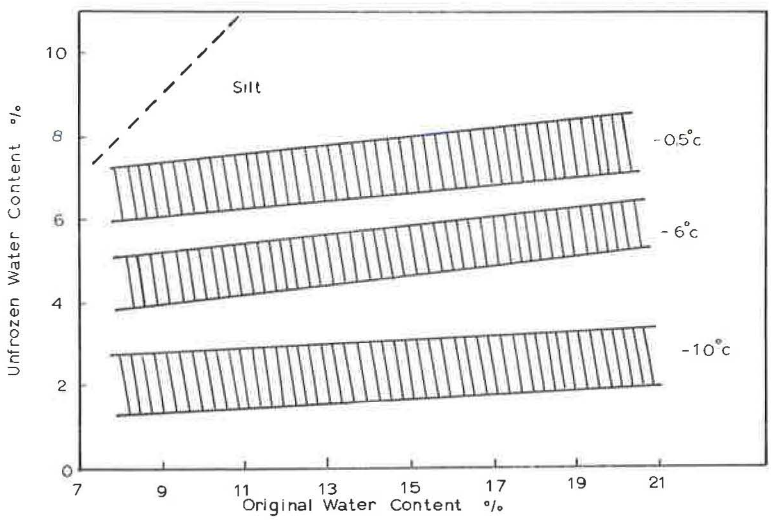

Figure 6. Unfrozen water content and original water content.

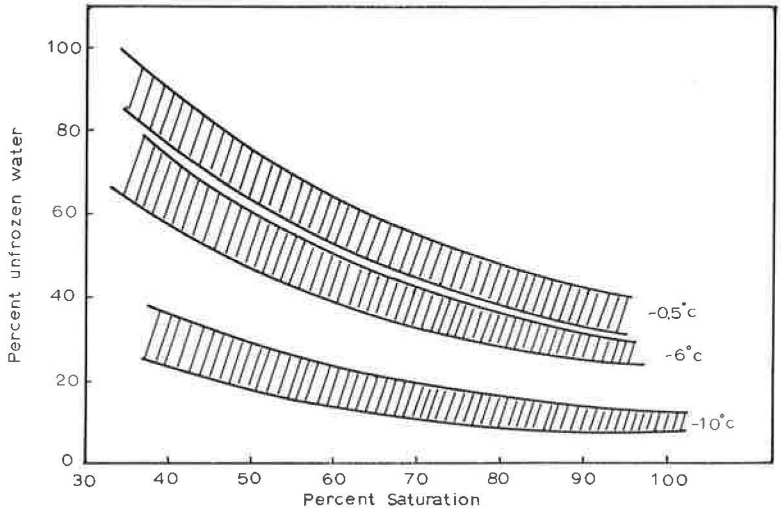

Figure 7. Percent saturation and percent unfrozen water.

Bearing in mind that the samples tested were not completely saturated, the average free energy difference then represents not only menisci or capillarity effects but also the interaction of the adsorbed water layers (as a result of long-range and short-range interaction). In essence, this average free energy difference is the total soil-water stress. It is possible to establish relationships between unfrozen water content or percent of unfrozen water with initial water contents or degree of saturation. Holding atmospheric pressure constant, with increasing initial water contents it follows that the percent unfrozen water will decrease because the average free energy difference of the soil water decreases with increasing water contents. Hence unfrozen water content must also increase with increasing initial water contents because these are all referenced to the same quantity of solid particles. The statement of significance therefore is that as moisture potential decreases, i.e., if the average free energy difference of the water in the soil decreases, the unfrozen water content increases and the percent of unfrozen water will correspondingly decrease.

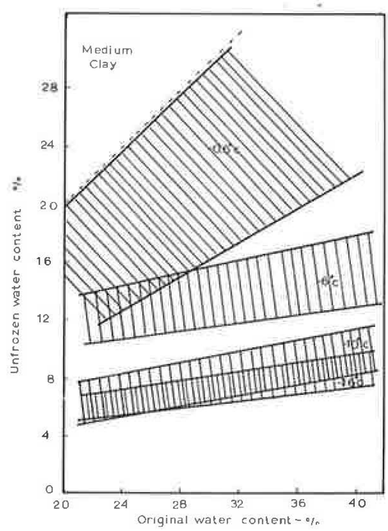

Figure 8. Unfrozen water content and original water content.

Figures 10 and 11 are an attempt to incorporate the saturation effect with initial water contents. This is done by multiplying the water content with the corresponding degree of saturation thus producing the saturation-water content parameter. Bell clay has been used with this method of treatment of unfrozen water content results. Here again, the relationships described reflect those previously shown. The scatter of results however is less since some portion of the error with saturation or water content has been accounted for with the use of the saturation-water content parameter.

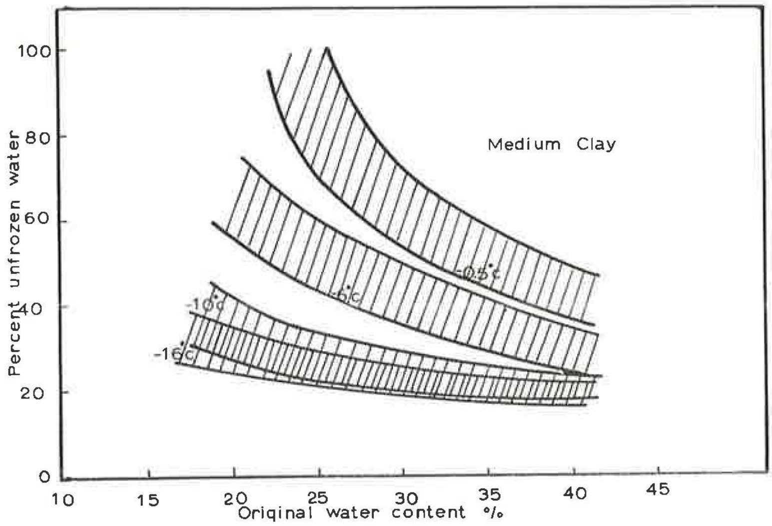

Figure 9. Original water content and percent unfrozen water clay.

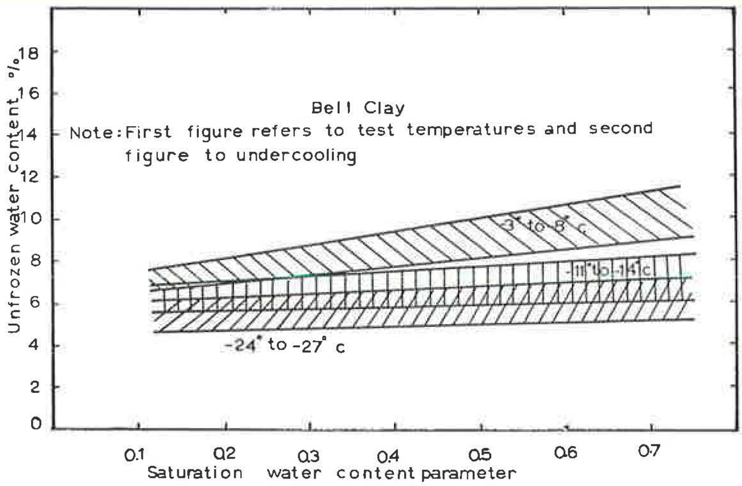

Figure 10. Unfrozen water content and saturation water content parameter.

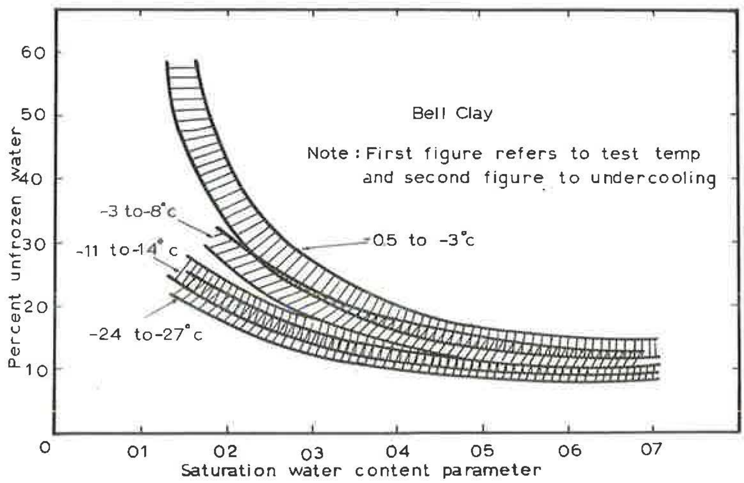

Figure 11. Percent unfrozen water and saturation water content parameter.

Soil Suction and Unfrozen Water

With measurements of both soil suction and quantity of water remaining unfrozen for a particular set of constraints, it is then possible to proceed to establish the interrelationships between soil suction, temperature, soil type and unfrozen water. These relationships may be presented in a variety of ways and Figures 12 through 15 demonstrate some of the more useful ways for gaining a better understanding of soil suction and unfrozen water.

For the medium clay and silt samples, the influence of temperature on unfrozen water content for a series of initial water content conditions is shown in Figure 12. If desired, soil suction or moisture potential may also be included with the water content values. These may be determined from Figures 4 and 5. These relationships seem to be contrary to the demonstrated results of other investigators (10) where unfrozen water content for a fully saturated soil is, under a given set of constraints, dependent only on the freezing temperature. The explanation may be found in the fact that the samples considered in this study were not completely saturated. Hence, considered in terms of total soil moisture stress, it will be obvious that for partially saturated soils, initial water contents would also influence unfrozen water content. Because of differences of configuration for partially saturated soils formed under laboratory

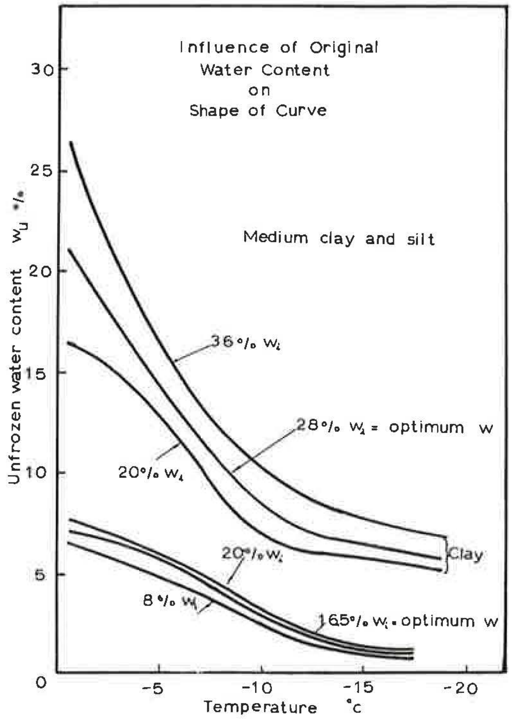

Figure 12. Temperature and unfrozen water content.

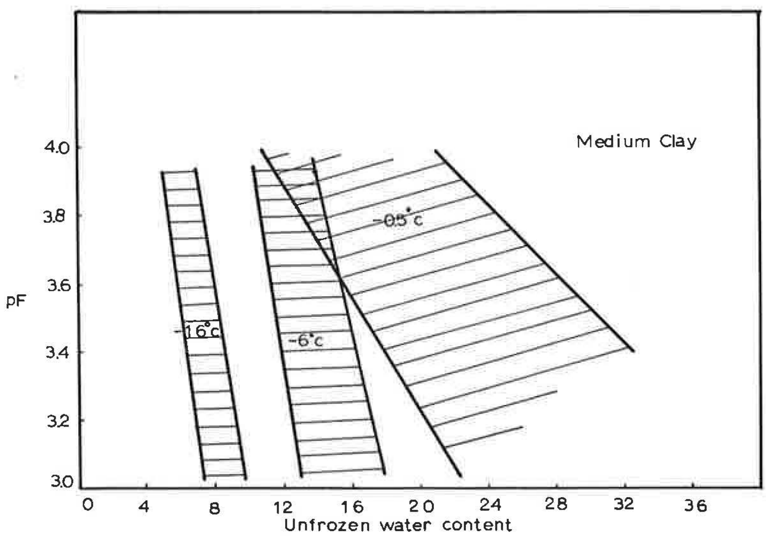

Figure 13. pF and unfrozen water.

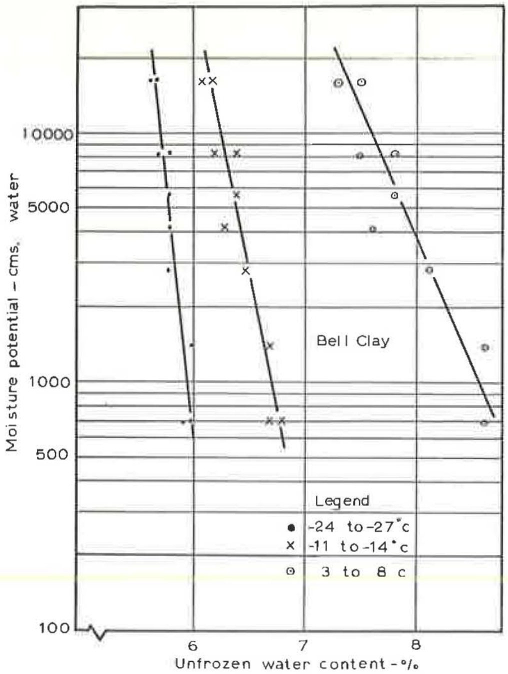

Figure 14. Moisture potential and unfrozen water content.

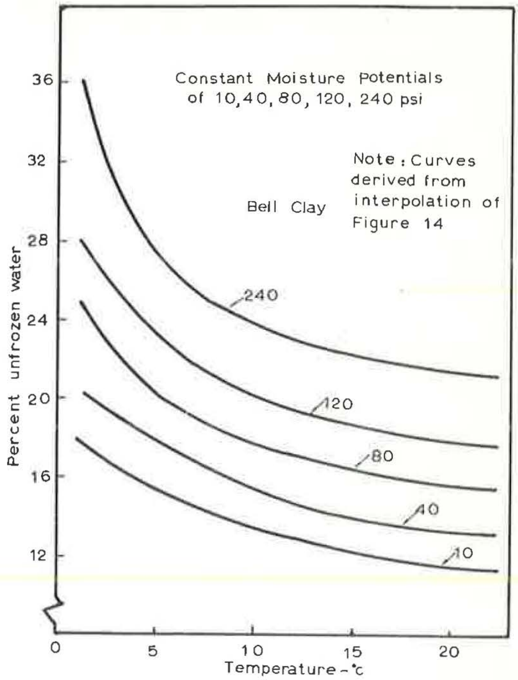

Figure 15. Percent unfrozen water and temperature.

conditions, there would correspondingly be different free energy relationships; this is evident from an examination of the desorption curves for (a) a slurry and (b) a dry-packed sample of the same soil.

The effect of freezing or thawing to the test temperature is shown in Figure 13 where soil suction is directly related to unfrozen water content for the medium clay samples where the right boundary of the bands represent freezing to and the left boundary signifies thawing to the test temperature. Once again, as in all the graphs using bands to portray the relationships shown, the scatter of results is evident. However, the patterns are well defined and the points are well bounded between the limits as stated previously. Figure 14 relates soil suction expressed as moisture potential to unfrozen water content for the Bell clay. Remembering that a decrease in free energy difference of the soil water produces upon freezing of the soil mass corresponding decreases in percent of unfrozen water, and further taking cognizance of the fact that re-arrangement of the arithmetic values will yield unfrozen water contents that will correspondingly increase, the interrelationships mentioned previously can be established. It is important to note that freeze-thaw history does influence the final determination of unfrozen water content. This may possibly be due to the reorientation of particles and other associated mechanisms. In this study, for the thawing portion, the soil samples were generally frozen to a temperature of about 3 C lower than the prescribed test temperature (or as shown in Figs. 10 and 11).

It is important to bear in mind that the relationships described heretofore pertain to measurements of moisture potential or soil suction at room temperature and that these have been used to correlate measured unfrozen water contents. The intention here is to be able to use measured soil suction values at room temperature to predict the quantity of unfrozen water for the soils tested. This would eliminate the necessity for measuring soil suction as a function of temperature—which is inmeasurably more difficult.

Choosing Bell clay as an example, the influence of temperature on the percent of unfrozen water for any one moisture potential or soil suction value may be seen in Figure 15. The moisture potentials were measured at room temperature and do not represent the moisture potential at the same subfreezing temperature. Preliminary tensiometer measurements (between 0 C and -3 C) for silt samples show that soil suction tends to increase as the temperature is lowered below 0 C. However, it is difficult to quantify this phenomenon exactly since one must necessarily consider the fact that there will exist a temperature gradient within the pressure measurement section of the tensiometer. Williams (6) has presented data, using the unique relationship of water content-dry density from oedometer tests, showing that soil suction increases as the temperature decreases from 0 C to -1 C. As verification of this, he has computed soil suction and temperature using the equation proposed by Schofield (2). However, if one bears in mind that this particular equation specifically relates soil suction to temperature depression, it becomes obvious that higher soil suction values must be reflected by greater temperature depressions in the soil water.

In order to relate effects of lowered temperatures on measured soil suction (quite apart from all the previous discussion on soil suction measurements at room temperature) it is necessary to consider contribution to soil suction from two major sources: (a) surface tension forces, and (b) Gouy forces. In the absence of ice formation, lowered temperatures would tend to increase the former and decrease the latter (11). Hence, it becomes necessary to think in terms of the algebraic addition of two quantities, i. e., one increasing and the other decreasing for the sum total demonstration of soil suction. It is possible to have systems where one would completely dominate the other. For silts, surface tension forces would dominate and for active clays, the reverse would be true. Since soil suction measurements performed at room temperature represent the total contribution of these forces for that particular temperature and since it is possible to evaluate the influence of temperature on the demonstration of these forces, it seems reasonable to expect that relationships between soil suction (measured at room temperature) and unfrozen water content can be established.

Acknowledging the relationship between moisture potential and temperature (and the preliminary tensiometer data for silts indicate that as -3 C is reached this relationship seems to become near constant), it is evident that it is possible to utilize initial moisture potential relationships in the study of unfrozen water. It can be noted (Fig. 15) that with increasing initial moisture potentials (i. e., measured at room temperature), the percent of unfrozen water content for any one temperature correspondingly increases. Since the moisture potential is a measure of the average free energy difference of the water in the soil mass, the relationship described may be used interchangeably in terms of room temperature measurements of moisture potential, soil suction or free energy difference of the soil water.

SUMMARY AND CONCLUSIONS

In this paper the terms soil suction (pF) and moisture potential have been used interchangeably. This was done by design because both represent the same measure of the free energy difference of the water in a soil mass. Based on previous studies, it becomes evident from a study of soil-moisture relationships that there could be similar relationships which would establish the phenomenon of partial soil freezing. It then follows that the dependence of unfrozen water in a frozen soil mass on the forces holding water to soil may be directly thought of in terms on a minimal number of parameters. This would bypass the necessity of obtaining an exact definition of the forces that hold water to soils, but would in essence establish a measure of the consequent action of these forces interacting in the soil-water system. The total potential of soil moisture is a useful tool. Although it does not require specific definition of the forces by which water is retained in soils, it permits one to measure the end effect in terms of a convenient parameter. The pressure membrane technique used in this study is relatively accurate if little or no particle reorientation occurs.

The results of this study indicate that the forces holding water to soil measured in terms of the soil suction capacity (pF), or as moisture potential at room temperature, may be used to relate unfrozen water content in partial soil freezing. In terms of moisture potential measured at room temperature, the results show that soil-water systems (and there is no specific requirement for complete saturation of specimens) with higher moisture potentials will upon freezing retain more unfrozen water—when compared to those with lower moisture potentials.

It is necessary to consider moisture potential in terms of specific contributions from surface tension forces and Gouy forces since temperature effects on these are not similar. Since it is possible to qualitatively evaluate the temperature effect on the demonstration of these forces, it then is further possible to summate these effects and use room temperature measurements of moisture potentials to predict unfrozen water contents for soils specifically studied.

ACKNOWLEDGMENTS

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