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RECENT DEVELOPMENTS IN LABORATORY FROST HEAVE TESTING OF SOILS

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ABSTRACT
This paper describes some recent advances in frost heave testing, suitable for a large scale project where several tests and freeze cycles can be carried out at the same time. Many test procedures freeze the soil too fast for practical field applications (i.e. chilled pipelines). Other shortcomings may include ignoring the side-friction component of stress, blockage of the drainage filter for water intake, inadequate permeability measurements to estimate suction at the freezing front, and only occasional water intake measurements. Each of these oversights involve a non-conservative assessment of the frost heave response of the soil.

A test procedure is described that addresses and rectifies each of these issues, and a demonstration series of tests on an artificial soil is carried out. Continuous evaluations of heave, water intake, frost depth, SP, suction and freezing rate are made using software written to accept the raw laboratory data. The results are presented in detail, and illustrate how the frost heave parameters required for design can be extracted from the data. The results are interpreted in terms of the Segregation Potential (SP) method, and also in terms of the Discrete Ice Lens approach.

RÉSUMÉ
Cet article décrit certaines avancées techniques récentes concernant le soulèvement dû au gel et applicables à un projet de grande envergure, alors que plusieurs essais et cycles de gel peuvent être effectués simultanément. Plusieurs procédures d’essai amènent un gel trop rapide du sol en regard des applications pratiques de terrain (c.à.d. pipelines refroidis). D’autres défauts peuvent inclure le fait d’ignorer la composante de friction latérale de la contrainte, le blocage du filtre de drainage de la prise d’eau, des mesures inadéquates de la perméabilité pour estimer la succion au front de congélation, et des mesures simplement occasionnelles sur la prise d’eau. Chacune de ces omissions implique une évaluation non conservatrice de la réponse de soulèvement dû au gel du sol.

Une procédure d’essai, qui tient compte et rectifie chacune de ces problématiques, est décrite, et une série d’essais de démonstration sur un sol artificiel est également décrite. Des évaluations continues du soulèvement, de l’apport en eau, de la profondeur du gel, du potentiel de ségrégation, de la succion et du taux de gel sont réalisées en utilisant un logiciel qui a été développé, afin d’accepter les données brutes de laboratoire. Les résultats sont présentés en détail, et illustrent comment les paramètres de soulèvement dû au gel, qui sont requis pour la conception, peuvent être extraits des données. Les résultats sont interprétés selon la méthode du potentiel de ségrégation, et également selon l’approche de lentilles de glace distinctes.

1 INTRODUCTION AND BACKGROUND

The main objective of laboratory frost heave tests is to define frost heave susceptibility of a soil under defined boundary conditions, including temperature, thermal gradient and overburden pressure. Applications for frost heave input data include seasonal freezing under highways, where the frost penetration rate is comparatively rapid, and long term freezing under cold pipelines, where the frost penetration rate is much slower. The same test data can be used for either application type, but the temperature boundary conditions and pressure ranges may be different.

There are a number of common oversights or shortcomings associated with laboratory frost heave programs in the past. Interestingly, these shortcomings all lead to an unsafe (non-conservative) result for the frost heave data. The first is side friction, resulting from shear interaction between the sample and the rigid cell walls. It has been estimated that side friction could lead to an equivalent vertical stress of up to 35 kPa. That is, there could be an additional and unknown vertical stress acting on the sample which is not added in to the overall applied stress. The first and simplest way to minimize this effect is to freeze the sample from the base upwards, and in this way the unfrozen section of the sample is displaced upwards in the cell, rather than the frozen section, which would have much higher side friction. The second way to minimize this is by the use of a greased rubber membrane around the sample, which also serves to provide a water seal at the top (unfrozen) side of the sample.

The second potential oversight is the use of adequate filter papers to limit clogging at the water intake side of the sample. For very fine grained soils, it is sometimes necessary to use a much finer filter paper, in concert with coarser filter papers to limit transfer of fine soil particles into the filter system. An automated water intake monitoring system such as that described later allows a continuous assessment of water intake to the sample, and provides supporting data for the heave rate data based on sample height.

Thirdly, many laboratory experiments have used a frost penetration rate that is much higher than the design application requires. If cold side temperatures are too cold, then a normal sample size freezes in a few hours, with high freezing rates, and heave rates may be affected accordingly.

And finally, a permeability test is necessary to calculate the suction at the freezing front from the Darcian water flow from the drainage side to the freezing front. This permeability may be different depending on whether water is flowing through previously frozen and thawed soil, or soil that has just been consolidated and never frozen. So some thought is required to determine the preferred sequence of freezing, thawing and consolidation prior to the permeability test.

2 TEST SETUP

The frost heave test set-up used here is comprised of the following components:

- Cell barrel – made of PVC, 100 mm ID, 125 mm OD and 190 mm high, with thermistor beads spaced at 5 mm apart.
- Base and top plates – made of aluminum, with fluid circulation lines, drainage lines and porous stones, and thermistors. The drainage lines are connected to a pressure control system with burettes or volume change devices for monitoring of water expulsion / intake during consolidation and freezing, and measurement of hydraulic conductivity.
- Temperature control jacket – with a fluid circulation system that has an accuracy of ±0.1°C to provide a constant temperature environment immediately surrounding the frost heave cell barrel (Figure 2). The jacket is insulated on the outside to minimize the influence of room temperature of the laboratory.
- Temperature control baths – capable of maintaining constant temperatures on the base & top plates and the temperature control jacket within ±0.02°C over a period of at least 5 days.
- Temperature measurements – thermistors and read-out device to an accuracy of ±0.01°C.
- Axial loading device – a dead weight hanger system that is capable of applying constant load up to 200 kPa.
- Axial displacement – measured using LVDT (maximum stroke of 50 mm) to an accuracy of 0.001 mm.
- Other measuring devices – digital weigh scale and volume change device.
- Data Acquisition system – a minimum of 20 channels. A variety of hardware/software combinations may be used in the DA system, provided that it is compatible with signal output from the thermistors, LVDT and the volume change device.

3 SOIL SAMPLE

The soil selected for the heave testing was an artificial soil made from a blend of pure Kaolin and a non-plastic silt, and had the following properties (see Table 1).

Table 1. Properties of Test Soil

Soil Index Property	Value
Water Content prior to consolidation	44%
Water Content after consolidation	20%
Liquid Limit	25%
Plastic Limit	15%
Plasticity Index	10
Specific Surface Area	19.6 m^2/g
Clay Fraction	25%
Percent Finer than 0.02 mm	70%

The complete grain size distribution is presented in Figure 1.

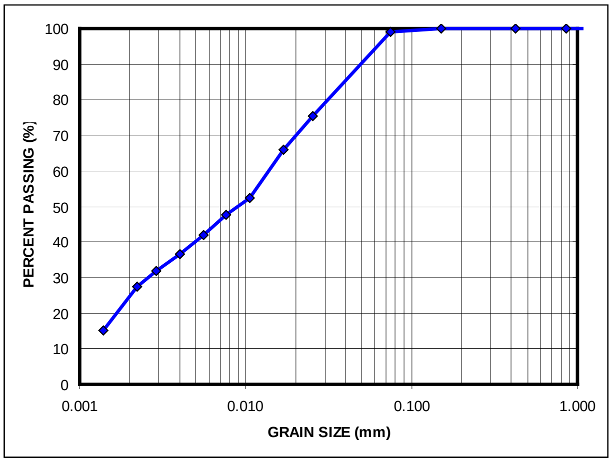

Figure 1. Grain Size Distribution of Soil

4 TEST SEQUENCE

4.1 Pre-testing

All thermistors including the top and base plates are calibrated using a circulating ice-water bath. Any malfunctioning thermistors are replaced if temperatures fluctuate greater than ±0.05°C during calibration.

4.2 Set-up and Sample Preparation

The soil slurry is mixed at a water content such that it is fully saturated but with no excess water, and de-aired using a vacuum. A rubber membrane is greased using high vacuum grease, in addition the inside of the cell barrel is greased, and the barrel is placed on the base plate. The membrane is stretched upwards, and folded down over the outside of the barrel.

A porous plate and two filter papers are placed on the base plate. A small amount of distilled water is placed in the cell, followed by the soil slurry sample until the soil slurry is approximately 12.5 cm above the base after tamping and gentle vibration to remove entrapped air. Some clear water is left on top of the sample. Two filter papers are added to the top of the sample, and for very fine soils, a third filter paper with very fine pore size (2 microns) can also be used.

With glycol hoses disconnected, the top plate is placed onto sample surface, and the membrane is stretched upwards around the greased perimeter of the top plate. Water is circulated through the top pore water inlet to de-air the water drainage lines. The glycol hoses are connected to the top platen. The drain line in the top plate is connected to a water storage container, whose weight is monitored continuously using a digital scale. The circulating jacket and insulation are assembled with the top plate and load piston guide bolted in place. The glycol lines to the circulating jacket/plate and the base plates are connected.

4.3 Saturation, Consolidation and Permeability Testing

The sample is consolidated to 200 kPa in load increments of 20, 50, 100 and 200 kPa. The over-consolidation will reduce unfrozen soil compression and to more closely represent naturally over-consolidated freeze history or glaciation. Changes in sample height, using a dial gauge and LVDT, and the volumes of water expelled from the sample with time are recorded as the consolidation proceeds under each load step. After unloading the specimen to 35 kPa, the hydraulic conductivity of the specimen is measured, using either a constant head method or by analysis of transient consolidation data. This step can also be carried out after the first freeze cycle, if a thawed soil hydraulic conductivity is considered more appropriate.

4.4 Frost Heave Testing

Glycol is circulated to the top & base plates and the jacket at +0.5°C for at least 24 hours, while consolidation is taking place. The temperatures from all thermistors are recorded once every hour over this period. The sample is nucleated by passing glycol at a temperature of –15°C to –20°C through the base plate for about 3 to 4 minutes. The dial gauge and burette should show a small sudden change (i.e. heave of about 0.05 mm) or so, and a small positive water expulsion when nucleation occurs. The base plate circulation is changed to –1.0°C (or the selected cold side temperature) to avoid losing ice crystals, and freezing continues from the base plate upwards.

Thermistors, the digital weight of water in the water intake container and the LVDT are read every 15 minutes with a DA system, and the dial manually every hour during working days. The sample is anticipated to approach thermal equilibrium after 2 days or so, but the frost heave test is continued for about 3 days. In order to increase the amount of useful data from the test, the end temperature controllers are used to "Ramp" the end temperatures downwards at -0.1 C/day, and this allows additional data at a near constant temperature gradient to be collected. This ramp phase can last for a further 3 days, for a total freeze cycle duration of 6 days.

If there is no heave or water migration after the first hour or so, the sample may not have been nucleated properly due to super cooling, and re-nucleation of the sample carried out after a day.

At the end of the freezing cycle, all circulations are shut off, and the sample is allowed to thaw for 24 hours. The second load is applied (i.e. 75 kPa), allowing consolidation and stabilization at +0.5°C. A permeability value can be calculated from the consolidation data prior to proceed with the next freezing cycle. The freezing cycles are repeated for 150 kPa, and finally a repeat test at 35 kPa. The specific loads used during freeze testing can be tailored to project specific requirements.

4.5 Post-test Measurements and Data Processing

The sample is generally removed from the cell after 4th freeze cycle, under frozen conditions. The final sample height and the height of the frozen portion are measured, and the total sample weight. The sample is photographed, split and photographed again, and water contents are measured on both the frozen and thawed sections. Grain size analyses and Specific Surface are measured on part of the sample tested. The post-test sample is stored for future considerations.

The test measurements (temperatures, vertical displacements, volume changes of water, etc.) are stored in a table form in spreadsheet, and the data are analyzed with a purpose built routine for interpolating between thermistors to define the frost depth and interpreting SP.

Test output with plots of heave, frost depth, and temperature gradient at the frost front versus time are prepared. The segregation potential (SP) can be calculated continuously with time from the data set, and correlated with rate of frost advance.

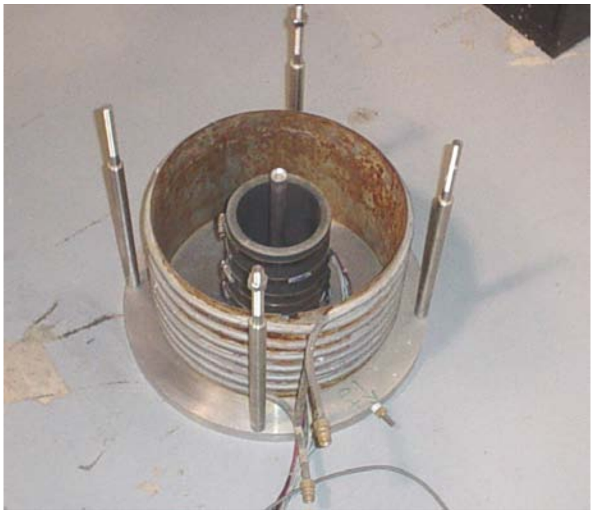

Figure 2. Cell Barrel Inside Temperature Control Jacket

5 TYPICAL RESULTS FROM FREEZE CYCLE

A typical series of results from the second test cycle (75 kPa overburden pressure) is included in the following charts.

First, the temperature profile through the sample as recorded by the cell wall sensors is plotted at several selected times through the 6 day test period (see Figure 3).

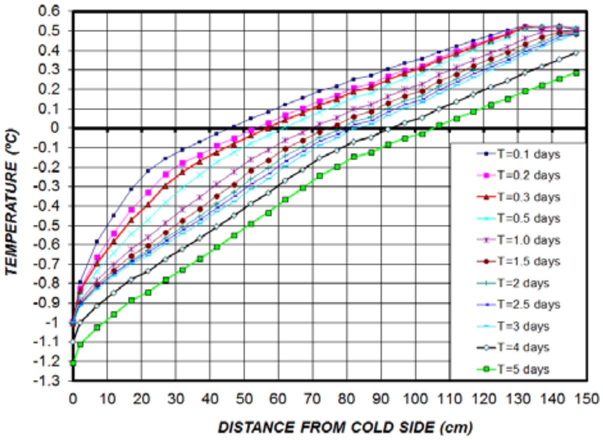

Figure 3. Temperature Profiles at Selected Times

The end temperatures and the interpreted temperature gradient at the freezing front are shown in Figure 4. The constant end temperatures for 3 days are evident, followed by the linearly decreasing (ramped) end temperatures for the next 3 days at -0.1ºC/day. The degree of temperature control appears very good, during both the constant and ramped end temperature phases.

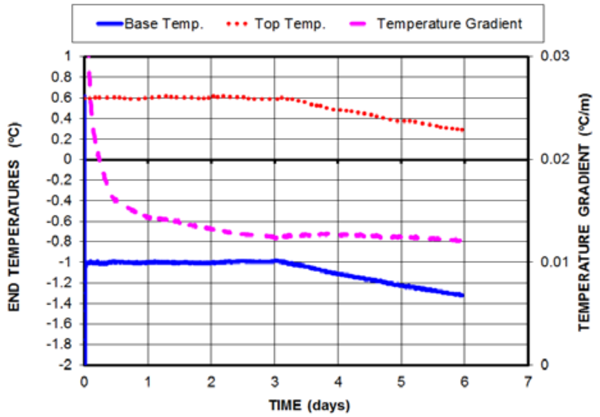

Figure 4. Specimen End Temperature and Temperature Gradient Variation with Time

Figure 5 shows the interpreted height of frost above the cold base plate, together with the height of unfrozen soil. The height of unfrozen soil is the sample height, minus the height of frozen soil. This is considered a more reliable indicator of frost advance into new unfrozen soil, as the height of frozen soil includes the frost heave, and can still be increasing even though there is no new frost advance into thawed soil. Of considerable interest is the comparison between the total observed heave, and the heave by water intake from the external water supply. Because water intake is monitored continuously by the data acquisition system, it can be continually compared with the total heave, providing a valuable check on the heave development. The small difference between the two curves is the 9% expansion of in-situ pore water, which for this soil is quite small compared with the heave due to water attracted to the freeze front.

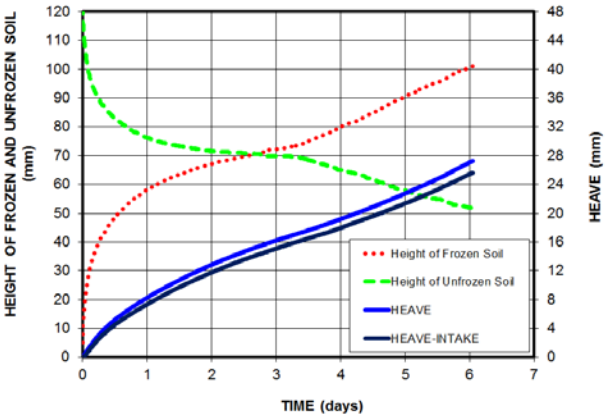

Figure 5. Heave with Time

As heave rate and temperature gradient at the freeze front are both continually evaluated, the SP parameter is continually calculated (see Figure 6). There is considerable variation in the parameter, due to changing thermal and hydraulic conditions.

The strongest dependence appears to be on the frost penetration rate into new unfrozen soil. As this freezing rate falls off and approaches zero, the sample is approaching thermal equilibrium, and the SP falls continuously. At some high freezing rate of 30 mm/day, say, the SP reaches a peak value of about 400 mm^2/day·ºC. This freezing rate is too high for many design applications such as pipeline design. At a low freezing rate of 2-5 mm/day, the SP falls closer to about 300 mm^2/day·ºC, a value more suitable for field design applications.

During the second (ramped) end temperature phase, the SP rises again towards about 360 mm^2/day·ºC, for a frost advance rate of 5-10 mm/day.

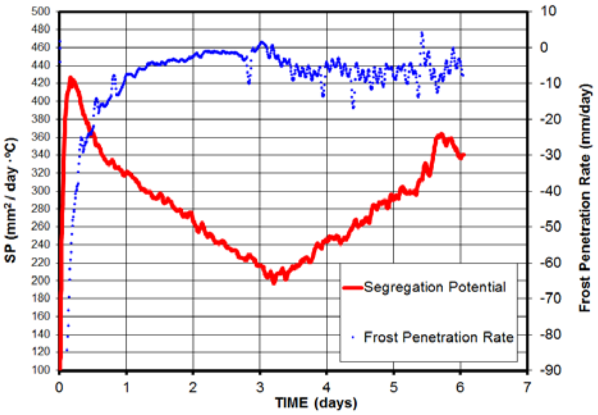

Figure 6. Segregation Potential and Frost Penetration Rate with Time

Finally, the interpreted suction at the freezing front is plotted continuously with time on Figure 7. The suction is calculated from the water intake velocity and the measured permeability for the thawed sample. The length of unfrozen soil is continuously changing, and the calculated suction takes this into account.

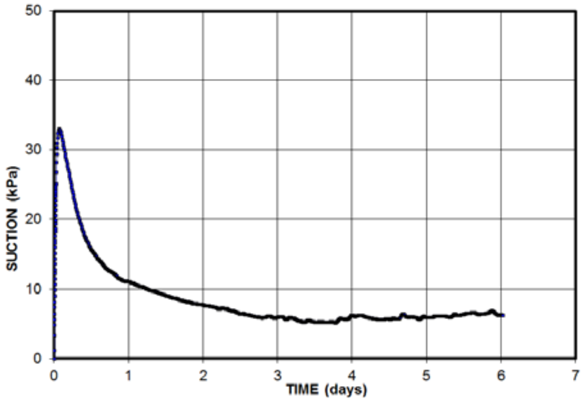

Figure 7. Variation of Suction with Time

The suction for this soil is relatively small, dropping to 10 kPa or less after a day of freezing. In this approach, suction and overburden pressure are combined as an effective stress, and there is theoretical support for doing this (Nixon, 1991) in the Discrete Ice lens approach. Konrad and Morgenstern (1982) tend to treat the overburden stress and suction separately, which makes the interpretation of test data and the application of data in design more complex.

The following is a picture (see Figure 8) of the Kaolin-silt sample at the test series conclusion. The sample base (cold side) is at the base of the picture. The classic smaller, closer spaced ice lenses are apparent resulting from the faster freezing rates early in the test. As the freezing rates slow, the lenses become bigger and more widely spaced. Close to the end of the sample, a very large ice lens is seen, corresponding to much of the observed frost heave in the later phase of the test.

Figure 8. Close Up Photograph of Ice Lenses at End of Test

The sample is also sectioned into 10 mm horizontal disks, and water contents measured for each disk. A water content profile can then be established for the sample. This profile is aligned vertically with the observed sample ice features on the next graph, showing the high water contents that might be expected for the icier areas of the sample (see Figure 9).

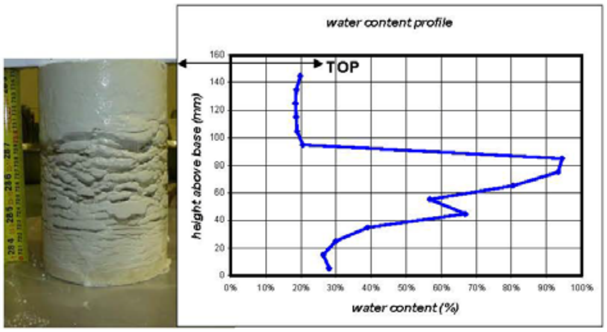

Figure 9. Side by Side Comparison of Post Heave Sample and Water Content

6 SUMMARY OF HEAVE PARAMETERS WITH PRESSURE

A brief summary of the heave parameters using two methods are presented below.

(a) Segregation Potential Method

A summary of the interpreted heave parameters using the SP method and the background information for stress, freezing type, cold side temperature are given on Table 2.

Table 2. Summary of Heave Parameters

Cycle	Test Name	Applied Load (kPa)	Time (day) for SP Interpretation	Suction (kPa)	Eff. Stress (kPa)	SP (mm^2/day·°C)
KS-1	Constant-1	35	1.3	13.5	48.5	340
KS-1	Ramp-1	35	6	8.1	43.1	340
KS-2	Constant-2	75	1.8	8	83	280
KS-2	Ramp-2	75	6	6	81	340
KS-3	Constant-3	150	1.7	6.6	156.6	220
KS-3	Ramp-3	150	6	3.4	153.4	210
KS-4	Constant-4	35	1.1	9	44	280
KS-4	Ramp-4	35	6	5	40	290
KS-5	Constant-5	35	1.2	8.4	43.4	200
KS-5	Slow Ramp-5	35	11	3.6	38.6	200

Typically, the SP parameter is plotted with pressure on a semi-log plot, as shown on Figure 10. For graphical presentation, "pressure" is defined as applied overburden pressure, minus the suction. As the suction is a negative number, the pressure is usually greater than the applied overburden pressure.

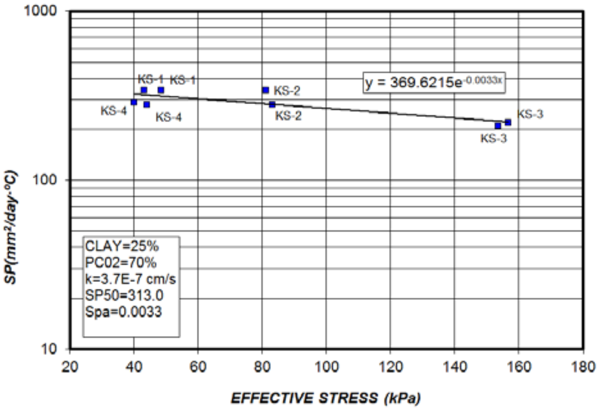

Figure 10. Summary of SP Results for Four Cycles

Using a best fit from a regression analysis, the SP - pressure relationship is shown on the above chart. This can be used in thermal-frost heave predictions for the design of chilled structures on initially thawed ground.

(b) Discrete Ice Lens

Equation 1 suggests a method for plotting frost heave data was advanced by Nixon (1991), to obtain the two parameters Ko and α in the frozen fringe permeability equation.

$$K = Ko/(-T)^{\alpha}; \quad Ko \text{ in cm/sec, and T in degrees C} \qquad [1]$$

These parameters are central to frost heave predictions using the Discrete Ice Lens method.

The data are plotted in the recommended form are presented in Figure 11, and a statistical power law fit is obtained.

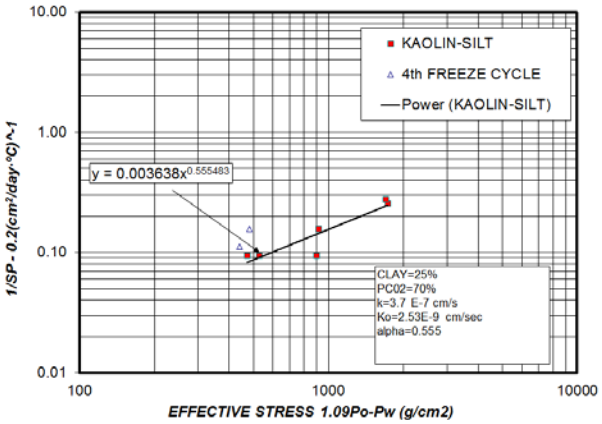

Figure 11. Discrete Ice Lens Heave Parameters

Equation 2 shows the relationship for frozen permeability is obtained to be

$$K = 2.53 \text{ E-09} / (-T)^{0.555} \quad \text{(cm/sec, degrees C)} \qquad [2]$$

and this can be used for frost heave predictions based on the Discrete Ice Lens method (Nixon, 1991).

7 SUMMARY AND CONCLUSIONS

Procedures are presented for laboratory frost heave testing suitable for a large scale project design. Some common oversights are reviewed and suggestions for minimizing some non-conservative aspects of the tests are presented specifically:

- the importance of minimizing side friction,
- preventing clogging of the drainage boundary,
- maintaining slow freezing rates and
- continuously monitoring water intake are stressed.

A typical set of results from one 6-day freezing cycle are presented, together with continuous interpretations of frost depth, temperature gradient, suction and SP with time. Selected SP values are plotted with effective stress, in a form suitable for frost heave design purposes. A typical relationship between SP and effective stress on a semi-log scale is obtained. An alternative interpretation based on Discrete Ice Lens theory is also provided.

8 ACKNOWLEDGEMENTS

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