

Reducing Frost Heave by Electro-Osmotic Dewatering and Soil Chemical Treatment

by Grant C. Baker and John C. Berg

INTRODUCTION

Frost heaving refers to soil expansion caused by the formation of ground ice in excess of the pore volume. It is associated with silty, fine-grained soils such as those found in the area of Fairbanks, Alaska. The widespread destructive consequences of frost heaving are well known. Both the expansion of soil during freezing and the loss of soil strength during thawing can destroy building foundations, roadways and airfields.

Excessive ground ice is able to form because large amounts of water move to the freezing zone during the freezing period. Although the exact mechanism for the water movement through the porous soil matrix to the freezing region is not known, we do know that for frost heaving to occur, three conditions must exist simultaneously:

- 1) a "frost-susceptible" soil (generally a soil containing at least 2 percent by weight fines smaller than 20 microns in diameter),¹
- 2) a prolonged period of freezing temperatures, and
- 3) an adequate water supply.

The freezing point of water, when confined to very fine capillaries, is substantially lower than that of bulk water.¹ Thus the fineness of frost-susceptible soil makes possible the transport of water as liquid through the soil to the freezing front where ice lenses form during the freezing period.

The specific requirements for frost heaving to occur suggest a number of methods to reduce or prevent it. One method which has shown promise is the treatment of the soil with chemicals which alter its frost susceptibility. Both flocculants and dispersants have reduced heaving in laboratory and field tests.^{1,2} Flocculants are thought to increase the effective particle size in the soil (so that nonsegregated freezing would occur without liquid transport), while dispersants are believed to stabilize the fines so that they are swept into the flow channels, causing clogging. A potentially promising, but untried, pro-

cess for frost heave reduction is soil dewatering by electro-osmosis, either before or during the freezing period. Electro-osmosis has been used since the early 1900s for dewatering peat and clays, and more recently by Sprute and Kelsh^{3,4} for the dewatering of mine sludges in northern Idaho.

BACKGROUND

Almost all soil particles in contact with water carry an electric charge. It can be negative or positive, but it is usually negative. The negative charge results from the preferential adsorption of anions (hydroxyl ions, if none other are present) which are generally smaller, less hydrated and more polarizable than the cations present. The behavior of a soil particle in suspension is strongly influenced by the charge on its surface, which results in the accumulation of neutralizing, oppositely charged ions (counter-ions) in the layer of solution immediately surrounding the particles (Fig. 1). The "cloud" of counter-ions consists of two layers. The first of these is an

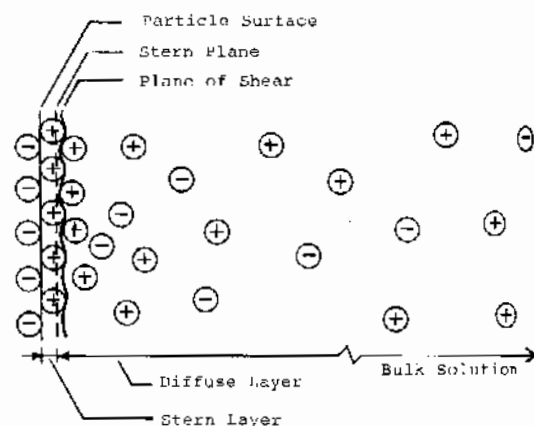


Figure 1. Ion distribution at and near the soil particle surface.⁵

adsorbed, compact monolayer of ions, termed the Stern layer, which usually partially neutralizes the surface charge. It may, however, either intensify or reverse the surface charge if the ions are specifically adsorbed (i.e., adsorbed due to forces other than electrostatic ones). The net resultant of the surface charge plus Stern layer charge is then neutralized by an array

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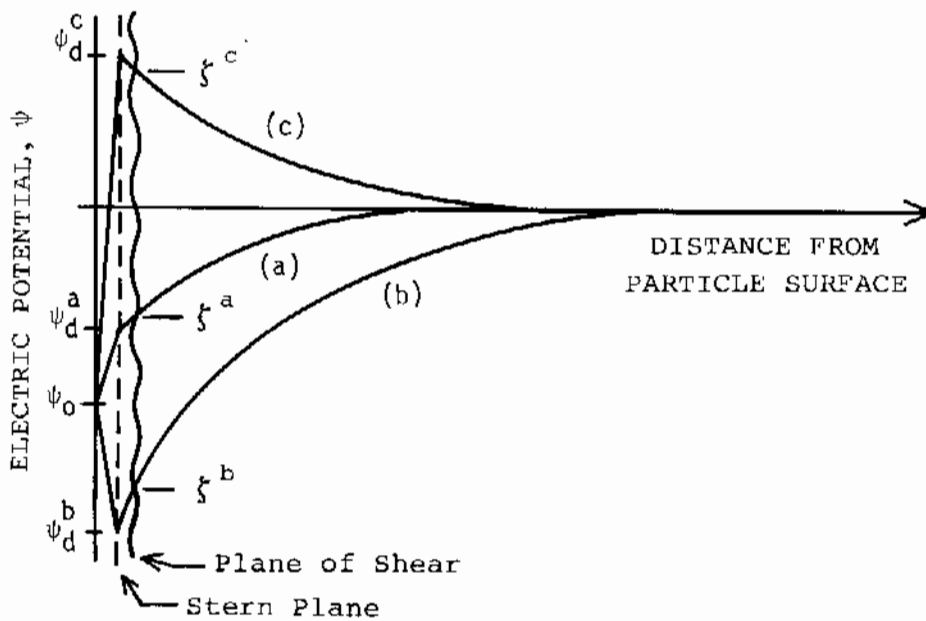


Figure 2. Effect of the adsorption mechanism on the Stern and zeta potentials. (a) Reduction in zeta potential due to preferential cation adsorption. (b) Increase in zeta potential due to preferential anion adsorption. (c) Reversal of sign between the surface and zeta potentials due to adsorption of strong polyvalent cations.⁵

of counter-ions farther away from but in the immediate vicinity of the soil particle surface. This outer stratum is called the diffuse, or Guoy, layer. The entire assembly of ions extending from the particle surface to the outer edge of the diffuse double layer is termed the electrical double layer.

Usually the concentration of counter-ions is highest close to the particle surface. At greater distances, the effective particle charge decreases, and the concentration of counter-ions decreases until it becomes the same as in the surrounding bulk solution. The surface potential, ψ_0 , is the electrostatic potential difference between the particle surface and the surrounding bulk solution. As the distance from the particle surface is decreased, the potential decreases linearly from the surface potential to the Stern potential, ψ_d , and decays approximately exponentially from the Stern potential to zero in the diffuse double layer, as shown in Figure 2.

The Stern potential is an important parameter in determining the extent of soil particle interactions. When it is of sufficient magnitude, and the diffuse double layer is sufficiently thick, the soil particles will experience electrostatic repulsion when they approach one another and the diffuse portions of the double layers begin to overlap. This prevents them from ap-

proaching close enough to one another to flocculate. Such a dispersion is said to be "stable." When electrolyte is added to the system, the diffuse double layer becomes much thinner, i.e., "collapses," and the dispersion may be destabilized and flocculate. While the double layer thickness may be computed if the ionic content of the surrounding solution is known exactly, the Stern potential cannot be measured directly.

Fortunately, there is a measurable parameter which permits the assessment of the combined effects of Stern potential and double layer thickness and thus serves as a reliable indicator of the state of electrostatic stability of the particles. This is

the zeta potential, ζ .⁶ It is the electric potential at the hydrodynamic "plane of shear" around the particle, a surface located generally just outside the Stern plane. It can be determined for small particles by tracking their electrophoretic movement in an electric field of known strength. When the zeta potential is low (less than approximately 10 millivolts), it is either because the Stern potential is low or because the diffuse double layer has been collapsed to a distance inside the shear plane, or both. From the standpoint of predicting the stability of the particles with respect to flocculation, it is immaterial. The only requirement is that the zeta potential is sufficiently small. A finite zeta potential is thus required for electrostatic stability of the dispersion and is also a requirement for the possibility of electro-osmosis, as described below.

Electro-osmosis refers to the flow which occurs when a direct-current electric field is placed across a porous solid mass that contains a connected network of moisture throughout its void space. When the field is applied, the (generally) positively charged mobile part of the diffuse double layer migrates toward the cathode and carries with it the associated pore water (Fig. 3).

The electro-osmotic flow rate is given by:

$$V = \epsilon E \zeta / 4 \pi \eta \quad (1)$$

where V is the linear flow velocity, ϵ is the dielectric constant of the water, E is the voltage drop per unit length along the flow path, η is the water viscosity, and ζ is the zeta potential. The zeta potential thus plays a key role in determining the potential effectiveness of electro-osmotic dewatering.

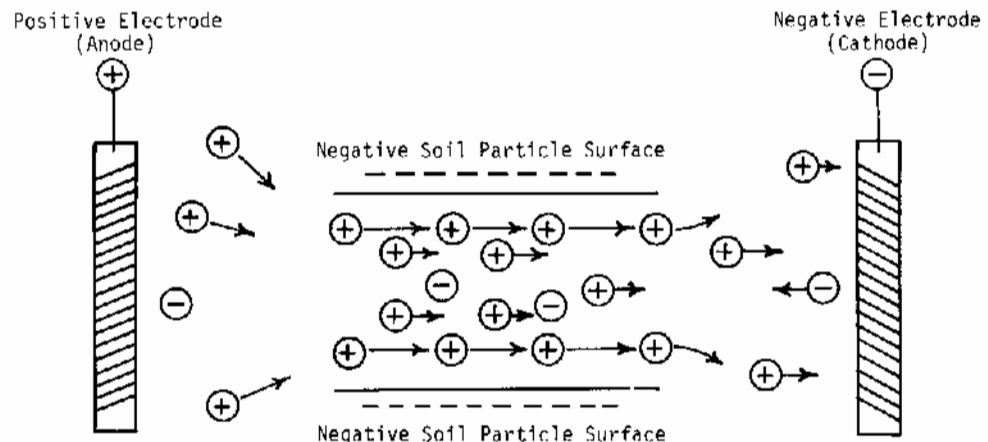


Figure 3. Illustration of electro-osmotic flow in an electric field.

tering. The addition of flocculants or dispersants is expected to produce significant changes in the zeta potential by altering the Stern potential and compressing the diffuse double layer, and thus should strongly influence the electro-osmotic behavior of the system. The total volumetric dewatering rate will, in addition, depend on the pore structure of the soil matrix (permeability), and this too should be affected by the addition of chemical flocculants and dispersants.

METHODS AND MATERIALS

Both laboratory and field tests were conducted. Laboratory tests were performed at the Engineering Center for Surfaces, Polymers and Colloids at the University of Washington, Seattle. The field test site was located at the CRREL (Cold Regions Research and Engineering Laboratory) testing grounds on Farmers Loop Road near Fairbanks, Alaska. The tests were conducted in an area of known frost heaving to determine the effectiveness of electro-osmotic dewatering procedures for reducing frost heave.

The soil for the laboratory tests was taken from the field test site to assure consistency in soil properties for all tests. The soil is relatively fine-grained (Fig. 4) and contains about 38 percent fines (size less than 20 microns). The natural soil moisture content is approximately 29 percent of the dry-soil weight (all moisture

contents will be given as percentages based on dry-soil weight).

The chemical additives used in the soil treatments consisted of a flocculating agent, ferric chloride (FeCl_3), and a dispersant, tetrasodium pyrophosphate ($\text{Na}_4\text{P}_2\text{O}_7$ or TSPP). These chemicals were chosen for a number of reasons. Research by Lambe et al., indicated that these additives had successfully reduced frost heave at relatively low concentrations and cost.^{1,2} Both additives should have strong and opposing effects on the soil particle double layer, yet they proved equally effective in reducing frost heave.

Soil samples were taken before chemical treatment, after chemical treatment, and after dewatering. These soil samples were analyzed for moisture content, zeta potential, and particle size distribution, and were examined by scanning electron microscopy (SEM). Zeta potentials were measured using a Rank Brothers Model Mark II microelectrophoresis apparatus. Care was taken in each case to obtain zeta potentials in the actual filtrate taken from the moist soil so that the chemical content of the liquid in the electrophoresis test cell was identical to that actually existing in the dewatering system. Particle size distributions were obtained using a Leeds & Northrup Microtrac particle size analyzer, and scanning electron micrographs of the soil up to 700X were taken using JEOL Model JSM-25 scanning microscope.

The field test plots were surveyed at approximately two-week intervals for the one year period between November, 1981 and November, 1982.

EQUIPMENT AND PROCEDURES

Laboratory test models, measuring 6x6x6 inches, were constructed of ¼-inch-thick Plexiglas™, as shown in Figure 5. Two cathodes were placed in each test cell to assure good soil contact. The cathodes were constructed of 1-inch O.D. copper tubing, approximately 8 inches long. They were perforated with ⅛-inch diameter holes at approximately ½-inch intervals to allow for water collection and removal. The anode was a plate measuring approximately 6x6 inches, ⅛-inch thick, and constructed of a special nickel-alloy stainless steel to resist anodic oxidation.

All test soils were initially dried. The chemical additives were dissolved in distilled water to give the desired concentration. The solutions were then added to the dried soil to give a moisture content of 43 percent. After chemical treatment, the soil slurries were mixed thoroughly and allowed to soak for about 18 hours.

At the end of the soaking period, the slurries were decanted and placed in the test models. Electro-osmotic dewatering commenced with the application of a DC potential to give a constant current density of approximately 900 $\mu\text{A}/\text{cm}^2$ (about 0.21 amps current flow); the current density is defined as the current per unit cross-sectional area perpendicular to the moisture flow. Electro-osmotic dewatering was stopped when its rate reached zero.

The field test plots measured 24x24x30 inches deep and had essentially the same design as the laboratory models, except that only one cathode was used. It consisted of a 2.5-inch O.D. perforated iron pipe, two feet long. Standard galvanized wire fencing was used as the anode. The test plots were spaced approximately ten feet apart to provide isolation from one another, yet close enough to ensure nearly identical soil conditions.

The field test site consisted of five test plots. One (Plot 5) was not disturbed in any way, and served as a reference. Plot 1 was prepared for dewatering but was neither dewatered nor chemically treated, and thus served as a second reference. Plots 2,

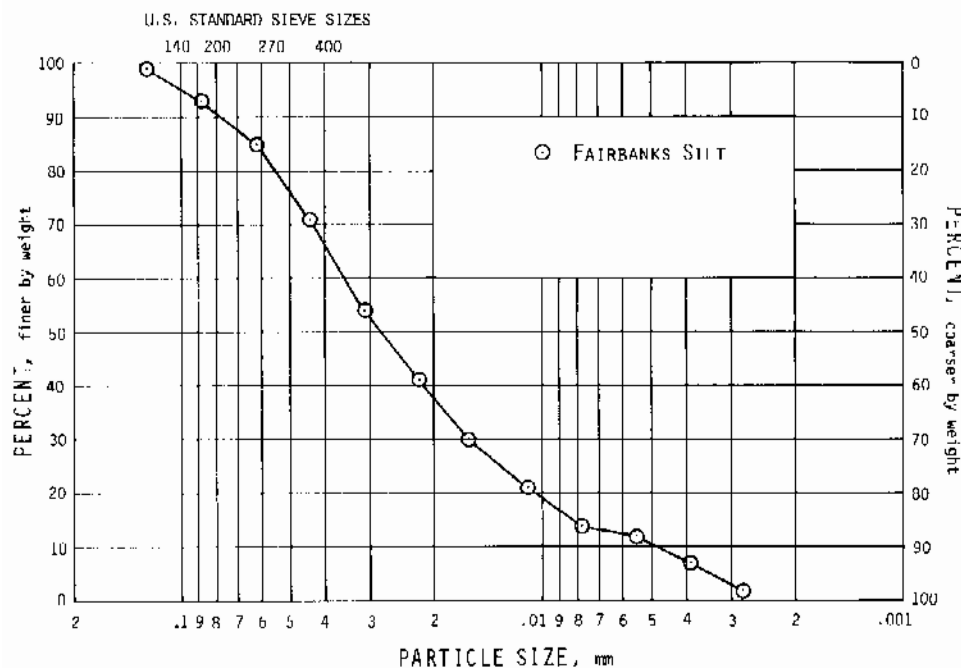


Figure 4. Particle-size distribution for Fairbanks silt test soil.

3 and 4 were prepared for dewatering, chemically treated and dewatered. Plot 3 was treated with TSPP, while Plots 2 and 4 were treated with FeCl_3 . Plot 4 was enclosed with a VisqueenTM plastic membrane to isolate it from outside water sources.

Twenty-six gallons of 0.1 M (Molar) FeCl_3 solution were added to each of Plots 2 and 4, and a similar amount of 0.06 M TSPP was added to Plot 3. These amounts and concentrations assured that sufficient chemical would penetrate into the interior of the test area. The solutions were allowed to percolate naturally down through the soil for about one week. Dewatering was then completed over a three-week period prior to freeze-up. The voltage was varied to maintain a fairly constant current density of approximately $1000 \mu\text{A}/\text{cm}^2$.

Frost heave field data were obtained in the form of measured heave and thaw ratios. The heave ratio is the amount of heave (elevation increase) of the surface of the treated soil divided by the corresponding quantity for the reference (in this case, the average of Plots 1 and 5). The thaw ratio is the amount of settlement (difference between the highest and lowest elevations) during the thawing period relative to the reference. Elevations of all plots were determined at regular time intervals by means of standard surveyors' instruments relative to a permanent monument on the test site.

The destructive consequences of frost action in soils are due to both the heave during the freezing period and the settle-

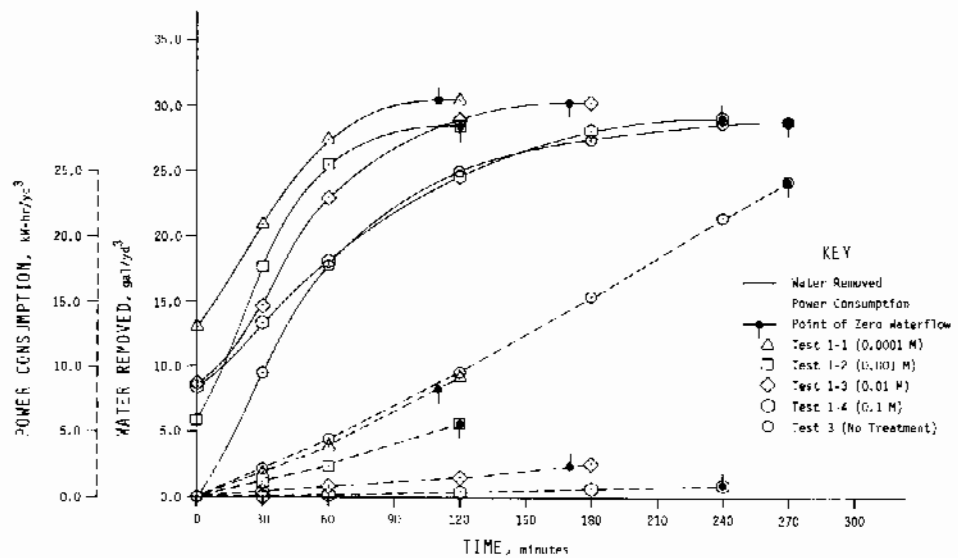


Figure 6. Dewatering and power consumption curves for laboratory tests using ferric chloride (FeCl_3) in soil treatment. Amounts of decant prior to electro-osmotic dewatering procedures are represented at time zero.

ment during the thawing period, so both heave and thaw ratios are important in the evaluation of methods for frost heave reduction. Electro-osmotic dewatering and chemical treatment may affect these ratios differently, and they both should be examined.

RESULTS AND DISCUSSION

Figures 6 and 7 give the results of the laboratory dewatering tests. The amounts of decant prior to electro-osmotic dewatering are included. Sprute and Kelsh showed that the excess or decanted water is the easiest to remove and requires a relatively small amount of power.⁴ The amount of

decant may also be affected by the type and concentration of chemical additive used. A comparison of the dewatering characteristics of the different tests should thus justifiably include the amounts of decant.

Generally all soil tests dewatered the same total amount, specifically to a moisture content of 28-30 percent. The notable exception was the test employing the 0.1 M TSPP treatment (Test 2-4). It stopped dewatering when the soil moisture content reached approximately 38 percent. This can be explained by the stabilizing effect of the dispersant which allows the smaller fines to be swept into the flow channels, causing clogging. In all cases, as moisture content reached its terminal level, the dewatering rates decreased dramatically.

The loss of permeability noted in the 0.1 M TSPP test would be a serious disadvantage for the practical application of such a dispersant during electro-osmotic dewatering. It is advantageous, however, with respect to slowing moisture movement to the freezing front in the absence of any prior dewatering. Thus, if dispersants are to be used in combination with electro-osmotic dewatering, the chemical dosing should be made *after* the dewatering has been completed.

A significant difference noted between the dewatering of the chemically treated and untreated soils was the increase in dewatering rate observed for the treated systems. For both the flocculant and the dis-

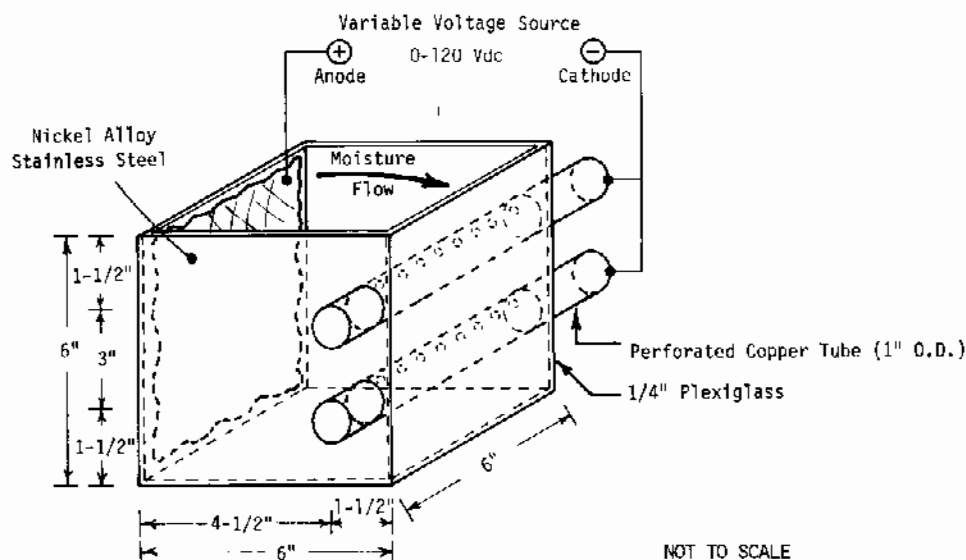


Figure 5. Laboratory test model schematic.

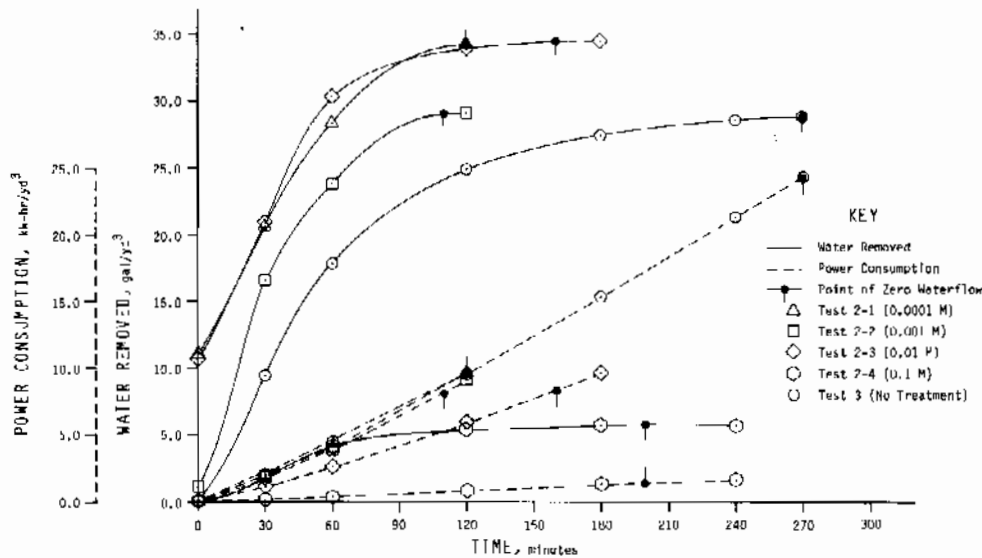


Figure 7. Dewatering and power consumption curves for laboratory tests using tetrasodium pyrophosphate (TSPP) in soil treatment. Amounts of decant prior to electro-osmotic dewatering procedures are represented at time zero.

persant, dewatering was completed in about half the time required for the untreated soil (approximately 120 vs 240 minutes). This might be partially explained as follows: The addition of a small amount of salt can be expected, first of all, to enhance the negative zeta potential of the soil particles through preferential adsorption of the unhydrated anions. Such a change in zeta potential did occur and is revealed in Figure 8, which shows the re-

sults of zeta potential measurements for all the conditions of the testing. The soil in contact with its natural ground water had a zeta potential of -16.0 mV, and the chemical treatment with both FeCl_3 and TSPP at the 0.0001 M concentration level increased it further (larger negative values) to -22.8 mV and -20.0 mV, respectively. Equation 1 suggests that the rate of electro-osmotic dewatering should increase in direct proportion to both the (negative)

magnitude of the zeta potential and the electric field strength, other factors remaining the same. The increased zeta potential may thus explain the increase of dewatering rate with small amounts of salt addition of either type.

As salt concentrations increased, the electric field strength, E , decreased (since current density remained constant), so dewatering rates decreased slightly, as might be expected. It is puzzling, however, that a greater divergence in behavior between the FeCl_3 and TSPP cases was not observed in this respect, since the effect of the two salts on the zeta potential was opposite. It would be expected that the dewatering rates of the FeCl_3 runs would decrease more sharply with increasing salt concentration than those of TSPP. In particular, it would be expected that when the zeta potential approached zero, as when FeCl_3 concentration reached 0.1 M, electro-osmotic dewatering rates would approach zero. Apparently soil permeability assumes an overriding importance. The flocculating action of the FeCl_3 prevents clogging of the flow pathways leading to high permeability, so that even under conditions of low zeta potential, dewatering rates are significant. The TSPP promotes clogging action, so that increased zeta potential is offset by decreases in permeability.

Another observation is that for both types of chemical treatments, the amount of power required for dewatering significantly decreased with increasing levels of chemical treatment. This reduction is traceable to the increased electrical conductivity of the soil water when salt is added. Since the tests were conducted at constant current density, the required voltage was decreased with salt addition.

The results of the particle size analyses and scanning electron micrographs of treated and untreated soil samples were inconclusive but suggest that any detectable (involving fines larger than approximately 0.1 micron) changes in particle size attributable to chemical treatment were not significant. The mechanism by which changes in stability affect dewatering rates thus depends on changes in the particle-particle "stickiness" or adhesion without altering the geometry of the particle structure.

Evaluation of the field frost-heave tests is based upon the measured heave and thaw

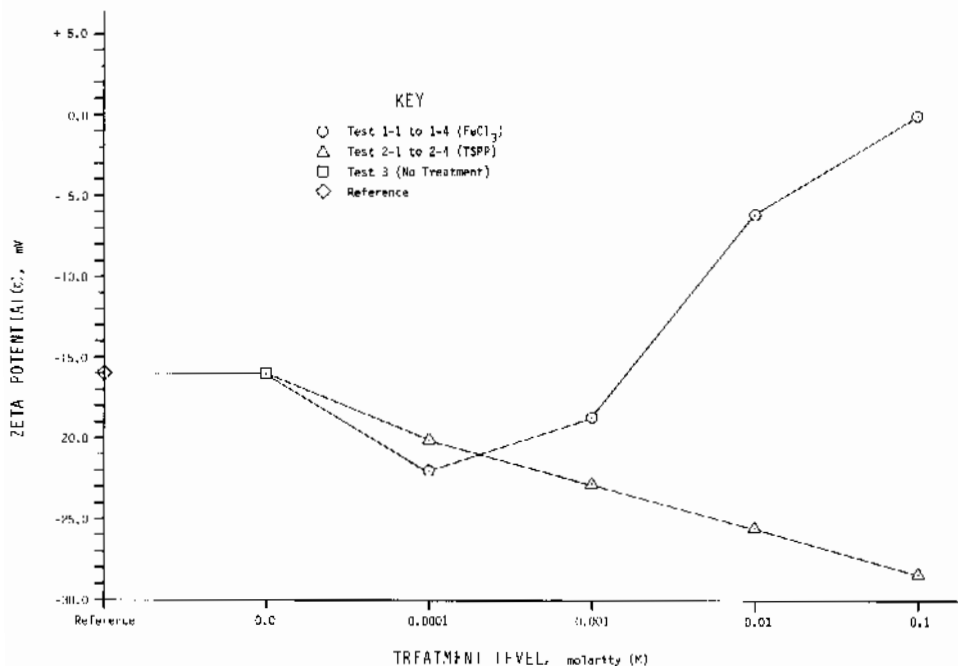


Figure 8. Comparison of laboratory zeta potential results for ferric chloride and tetrasodium pyrophosphate treated soils.

ratios, as shown in Table 1. Ratios less than unity indicate improvement, whereas ratios greater than one indicate impairment. Plots 1 and 5 were neither dewatered nor chemically treated, and the average of their freeze and thaw behavior was taken as the reference against which the chemically treated, dewatered test plots were evaluated. The difference in behavior between the two reference cases was 15-20 percent, giving a statistical measure of the reproducibility of the other tests, which were not repeated in the current work. Plots 2 and 4 show the positive results obtained for ferric chloride treatment with dewatering, Plot 4 differing from 2 in that the soil in Plot 4 had been dug up and reconstituted, with a plastic sheet buried beneath it. Both tests show significant improvement with respect to both heave and thaw ratios. Plot 4, the isolated system, showed the best results, indicating that heave due to water transport from soil adjacent to the plots was a factor in the other tests. Plot 3 employed the dispersant TSPP with dewatering, and it also showed significant improvement in both ratios. In all cases there was consistency between the heave and thaw ratios, i.e., those tests yielding the greatest heave also yielded the greatest degree of settlement.

It is important to note that the test plots were installed only to a maximum depth of 30 inches. The active layer in the test area extends to a depth of about eight feet. The reduction in the amounts of heave and settlement are thus a reflection of only the top third of the active layer. This suggests that treatment of the entire

depth of the active layer may produce even greater reductions in the amounts of heave and settlement.

A possible side effect of electro-osmotic dewatering in this test series should be noted. The metal electrodes (particularly the anode) may have acted to conduct heat out of the soil during the winter (when the surface temperature is less than the soil temperature beneath the surface) and into the soil during the summer (when the temperature difference is reversed). This would have the detrimental effect of promoting both heave and settlement. These effects, if any, were apparently overridden in the tests run.

CONCLUSIONS

1. Electro-osmotic dewatering with soil chemical treatment can significantly reduce frost heave in soils such as Fairbanks silt.
2. The rate of soil dewatering is enhanced with the addition of low concentrations of either a flocculant or a dispersant.
3. High concentration levels of dispersant can significantly reduce the amount of water removable by electro-osmosis.
4. The addition of salts can significantly reduce the power consumption for electro-osmotic dewatering.
5. The anticipated changes in soil particle zeta potential were produced by the addition of ferric chloride and tetrasodium pyrophosphate.
6. Changes in macroscopic (>0.1 micron) particle size distribution are not

affected by the addition of a flocculant or dispersant.

RECOMMENDATIONS

Further study of the effects of a wider variety of chemical additives and soils on dewatering procedures should be made. Test plots should involve the entire active layer.

The related process of electrophoresis (movement of the negatively-charged particles toward the anode: the opposite of electro-osmosis) should be tested in conjunction with chemical treatment of settling ponds for the mining industry. The use of a low DC potential within the settling pond could greatly enhance the settlement rate of the very fine suspended particles. The rate would be greater in conjunction with appropriate chemical treatment (to increase zeta potential) at very low treatment levels. Further research should find the optimal levels with respect to cost and environmental factors.

ACKNOWLEDGMENTS

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REFERENCES

- ¹Lambe, T.W. and C.W. Kaplar. 1971. Additives for Modifying the Frost Susceptibility of Soils, Part I. CRREL Technical Report TR 123, Pt. I. Hanover, NH. 41 pp.
- ²Lambe, T.W., C.W. Kaplar and T.J. Lambie. 1971. Additives for Modifying the Frost Susceptibility of Soils, Part II. CRREL Technical Report TR 123, Pt. II. Hanover, NH. 44 pp.
- ³Sprute, R.H. and D.J. Kelsh. 1980. Slimes Consolidated at the Henderson Mine. U.S. Bureau of Mines, Report RI 8441. Government Printing Office, Washington, DC. 20 pp.
- ⁴Sprute, R.H. and D.J. Kelsh. 1974. Laboratory Experiments in Electrokinetic Densification of Mill Tailings, Part I. U.S. Bureau of Mines, Report RI 7892, Government Printing Office, Washington, DC. 72 pp.
- ⁵Shaw, Duncan J. 1980. Introduction to Colloid and Surface Chemistry, 3rd ed. Butterworths, Liverpool, England.
- ⁶Riddick, T.M. 1967. Control of Colloid Stability through Zeta Potential, Zeta-Meter, Inc., New York.

TABLE 1
Amounts of Heave and Settlement and
Heave and Thaw Ratios for Field Test Plots

<i>Test Plot Number (Type of Treatment)</i>	<i>Maximum Amount of Heave (inches)</i>	<i>Maximum Amount of Settlement (inches)</i>	<i>Heave Ratio</i>	<i>Thaw Ratio</i>
1 (Electrodes installed, no treatment)	4.79 (averaged)	5.95 (averaged)	1.00	1.00
5 (No treatment)				
2 (FeCl ₃)	4.00	4.75	0.84	0.80
3 (TSPP)	4.50	4.91	0.94	0.83
4 (FeCl ₃ , enclosed)	3.60	4.14	0.75	0.70