CHEMICAL ADDITIVES TO REDUCE FROST HEAVE AND WATER ACCUMULATION IN SOILS

G. H. Brandt, Dow Chemical Company

Soil waterproofing chemicals are known to reduce frost heave in soils, particularly when soils are dried; the present study demonstrates that these chemicals work in moist soils as well. The mechanism and limitations are partly defined in this paper. A model soil waterproofing compound, 4-tert-butylcatechol (TBC), was studied as representative of the general group. Water absorption to growing ice lenses was measured as an indication of frost-heave rates. Capillary conductivity was also measured and correlated to heave and treatability. As little as 0.01 percent TBC produced minimum ice lens growth and capillary flow in some soils. A-4 soils responded well to treatment, whereas soils containing more than 50 percent clay did not. A simple hydraulic conductivity test should be considered as a major soil frost-susceptibility criterion.

•FROST HEAVE in soils has been reduced through the use of chemicals from the broad classes of cementing agents, plugging agents, dispersants, waterproofing chemicals, and freezing-point depressants. These types of chemicals treat one or more of three conditions (freezing temperatures, a frost-sensitive soil, and a water source) necessary to produce frost heave. Cementing agents decrease frost sensitivity by bridging soil grains and by plugging pores. Freezing-point depressants, primarily sodium and calcium chloride, decrease the freezing temperature of matrix water. Waterproofing chemicals limit water absorption by soils and consequently interfere with the water supply. Dispersants destroy soil structure and allow clay grains to plug capillary pores.

Lambe (25) tested about 40 additives and estimated their potential as frost-heave modifiers. He rated dispersants and inorganic cationic aggregates as most promising because they are easy to apply, low-cost, and effective at moderately low concentrations. Lambe rated waterproofing agents somewhat less promising even though they were excellent for modifying frost heave. His judgment was based on the need for extensive drying once soils have been treated and because more than 0.5 percent of these additives was needed. These disadvantages no longer exist because more recently discovered waterproofing chemicals will limit water absorption in moist soils when added at a rate of 0.1 percent or less (4, 8-20, 22).

Specific chemical groups containing various hydrophobic substituents limit liquid water absorption by soil. These have been identified by extensive laboratory investigation, as reported elsewhere (4, 8-20). Among the many compounds tested, 4-tert-butylcatechol (TBC) is one of the most effective for silty and silty clay soils. TBC was being commercially developed for several years under the trademark Terbec soil stabilizer and during that time was placed in more than 25 test roads to treat highly frost-sensitive soils.

Some roads were constructed entirely from the native soil with a seal-coat overlay, whereas others were constructed with a gravel base and asphalt wearing surface overlying a water-repellent soil layer. When they were constructed with adequate thicknesses of gravel base, roads endured spring thaws with little or no damage. Exceptions normally could be traced to poor drainage during critical freezing periods. These field data prompted investigations of ice accumulation in TBC-treated soils to help define limiting conditions for adequate performance.

TBC is known to effectively limit liquid water adsorption by many soils, but it does not interfere with vapor phase transmission (21). In dry soils, this phenomenon is easily understood because chemicals like TBC change soil mineral grain surfaces from water wettable to water repellent. TBC changes the wettability of soils because the ortho-hydroxyl groups on the phenyl ring coordinate with aluminum ions on mineral grain surfaces in such a way that the hydrophobic tert-butyl group extends from clay surfaces (7). The apparent contact angle between such a treated mineral grain and water is sufficiently high such that positive pressures must be applied before water penetrates dry water-repellent soil matrices (1, 5, 6).

Moist soils also are changed significantly by TBC, but the mechanism is more difficult to isolate than for dry soils. One explanation could be that water films in capillaries are disrupted by hydrophobic chemicals, thus reducing the number of pores available for conducting water (21). Another explanation could be that absorbed hydrophobes introduce disorder into water layers around clay particles and into water in soil pores. The net effect is decreased affinity for water, which can be expressed as a decrease in osmotic repulsion among soil grains (2, 21). In the latter case, water migration would be slowed by thin moisture films rather than by disrupted capillaries. The first explanation seems to be an extreme case of the second because both require extensive alteration of water structure and of forces between water and soil grains.

METHODS

Numerous freezing tests can be used to characterize the frost sensitivity of soils and the influence of chemical additives. Most tests seek to rank soils in a relative order of frost susceptibility or to rank chemical treatments in a relative order of effectiveness. The needs in the present study were somewhat different, however, because limiting conditions for adequate chemical performance in the field needed to be defined. We needed to quantify frost heave as influenced by drainage, temperature gradient, chemical concentration, and soil type. We chose to follow ice lens growth at stationary freezing fronts rather than program temperatures for advancing fronts, and we monitored water absorption under fixed overburden pressures rather than using heaving rate or pressure.

Many separate runs were required to study the significant variables; each run required about 3 weeks. Consequently, an automated test was devised to minimize long, tedious manual labor and to greatly simplify data handling. Ice lens formation was followed by continuously monitoring water absorption and temperature profiles using an automated data system with punched-tape output.

A chamber was built to hold eight soil cores; each core was contained in a separate cell (Fig. 1). The selected arrangement corresponds roughly to an open soil system as described by Jumikis (23). Ceramic frits, with bubble pressures below a moisture tension of 150 cm, were mounted in an aluminum plate and were connected to water reservoirs to control moisture tension. Filter paper underneath the soil cores assisted water conduction across the core-frit discontinuity. Frit permeabilities were sufficiently high to supply water at unrestricted rates. Cores were jacketed by rubber membranes, surrounded by polystyrene foam and Styrofoam brand plastic foam, and capped with Saran Wrap brand plastic film to prevent moisture loss.

Cores were frozen from the top by coolant that was circulated through surcharge weights equivalent to 1 psi or approximately 1 ft depth of gravel base. As soon as the cores reached freezing temperatures, ice was nucleated with liquid nitrogen. Bottom temperatures were held above freezing by coolant that was circulated through a large aluminum plate. Zero isotherms normally were adjusted to the center of the cores, forcing ice lenses to grow 2 in. from the frits. Typically, top temperatures were adjusted to -3 C and bottom temperatures to +3 C, producing a temperature gradient of 0.6 C/cm between the bottom plate and the top surcharge weight. However, typical temperature profiles measured by thermocouples within the cores registered 0.4 to 0.5 C/cm. Temperatures were controlled within about ±0.15 C, corresponding roughly to the accuracy limits of iron-constantan thermocouples and the Pace zero-degree reference unit used in the temperature measuring system.

Water absorption was measured by using specially constructed syringe pumps capable of detecting a 0.01-cc flow (these have since been replaced by Statham Universal load cells). Voltage proportional to volume of flow was logged for 8 m using a data acquisition system. Thermocouples and flow meters were sampled hourly by the unit, although sampling intervals could be selected between 5 min and 8 hr. When a run was completed, an IBM 1130 computing system read the data from punched tapes, processed the data, and plotted temperature profiles and cumulative water absorption for each soil core. With this system, changes in temperature profiles can easily be compared and correlated with changes in water-absorption rate. Furthermore, the amount of water absorbed during capillary equilibration prior to freezing is known, and the absorption rate during early stages of ice lens growth can be determined from the cumulative plot. At the end of a run, moisture contents were determined for core segments. Average ending moisture contents were calculated for each core and could be compared to moisture absorption plotted by the computing system.

In the ice lens test, cores 5 by 10 cm (2 by 4 in.) were compacted at optimum using double-end loading and 500-psi pressure. TBC was added to these soils in the mixing water. About 4,000 ppm of this chemical are soluble in water at room temperature, but concentrations of 7,000 to 8,000 ppm are needed to treat most soils at 0.1 percent additive. Consequently, such emulsions must be shaken vigorously before being atomized onto soil. All cores used in the ice lens test were wrapped in plastic film and stored moist until used. Only a few cores were partially dried to observe the influence of drying on frost susceptibility of TBC-treated soil. Cores completely air-dried were never placed in the test because they re-absorb only small quantities of water and do not grow ice lenses. Furthermore, air-drying is never achieved in the field for subbase soil layers in humid climates.

Other tests were run in this study to aid the interpretation of the ice lens test data. Capillary flow and conductivity were determined by using apparatus similar to that used by Sharma and Uehara (29), which was initially devised by Nielsen and Bigger (27). Porous ceramic frits were placed at both ends of cores 2 in. in diameter and 1 in. high with a 1-psi surcharge weight on top. Water reservoirs were connected to the frits and adjusted to moisture tensions of 25 and 75 cm. The tension gradient forces capillary water to flow through the soil cores. Water loss from the reservoir set at a tension of 25 cm was followed by the use of Statham Universal load cells. Eight channels of capillary flow were logged on punched tape simultaneously with the ice lens test data and later processed by computer. A typical run would take 3 to 4 days.

Unconfined compressive strength is also given for selected soils as related to TBC concentration and curing conditions. Most soil cores were immersed at optimum moisture after a moist cure, but some were immersed after air-drying. Strengths were determined on cores 1.13 in. in diameter and 2.25 in. high, which had been compacted at optimum moisture and 500 psi.

Soils used in this paper are described in Table 1 and include five from Michigan, two from Iowa, and four from West Virginia. Sample numbers identify sample sources, while letter designations (e.g., 11-B and 11-C) indicate different samples from nearly the same source. Five soils are classed A-4, two A-6, three A-7-6, and one A-2-4. Several additional soils were run through the tests described in this paper, but they only tend to confirm trends established by the selected data. Several soil-type names are omitted because the sample was not taken within the normal soil profile but rather from the underlying parent material.

RESULTS

Ending Moisture Contents

Typical moisture profiles for TBC-treated and untreated samples are shown in Figure 2 for Iowa silt cores (soil 23-B). The two top bar graphs are based on cores exposed to a moisture tension of 50 cm and 0.5 C/cm temperature gradient for 25 days. Starting water contents are indicated by solid lines across bars, and average ending water contents are indicated by arrows above each moisture profile. Shaded bars designate increases in moisture content for core segments.

Ice lenses grew at similar depths for treated and untreated cores in the top pair. The unfrozen lower half of the untreated core contained about 20 percent water, essentially the equilibrium moisture content present at a tension of 50 cm. In contrast, the moisture in TBC-treated soil was depleted in the unfrozen soil, whereas it accumulated in the frozen portion. The average ending moisture contents for the untreated core was 11 percent higher than at the start, whereas it was only 1 percent higher for the TBC-treated core. Much more water accumulated in both treated and untreated cores when they contacted free water (Fig. 2). Average ending moisture contents were about 32 percent and 23 percent for untreated and TBC-treated samples respectively. Ice lenses were very prominent in both. Under these saturated conditions, water moved more easily through unfrozen TBC-treated layers to freezing fronts. Also, the fact that the ice lens was growing less than 1 in. above free water probably enhanced ice lens development in the treated sample because there was very little unfrozen water repellent soil to limit water migration.

Average ending moisture contents after ice lens growth are plotted in Figure 3 for many cores of Iowa silt, soil 23-B, exposed to moisture tensions ranging from 0 to 150 cm. For untreated and treated cores alike, more water accumulated while the cores contacted free water than at tensions of 10 cm and more. However, there appeared to be very little difference in total water accumulation between tensions of 10 and 150 cm. TBC-treated samples consistently contained 7 percent less water than untreated samples at all tensions.

Soil moisture data from a field test road in Iowa compare roughly to the data shown in Figure 3. Many soil cores were taken immediately after spring thaw from a 3-year-old road. Moisture content of TBC-treated soil layers ranged between 14 and 19 percent, whereas comparable untreated layers ranged between 20 and 25 percent, a 6 percent average difference. Other field installations have been sampled after several winters of freeze-thaw, and moisture contents always have been slightly above optimum moisture for TBC-treated soils.

Most experiments began with cores at optimum moisture. Drier water-repellent soils should be expected to limit ice lens formation even more than moist soils. Consequently, Iowa silt cores (23-D) were dried back slowly in a constant humidity cabinet before being placed in the freezing chamber. Untreated cores began at 8.8 and 9.5 percent water before being exposed to tensions of 0 and 50 cm respectively. After exposure to a temperature gradient of 0.6 C/cm for 21 days, they contained 30.8 and 24.4 percent water respectively, but about 26 and 21 percent of that was absorbed by capillarity before freezing began, as indicated by the bottom moisture content bars for unfrozen soil shown in Figure 4.

Both TBC-treated cores began the experiment at 6.2 percent water (bottom, Fig. 4). Average ending water contents were 9.8 percent and 8.7 percent respectively for tensions of 0 and 50 cm, thereby increasing 3.6 percent and 2.5 percent. Ice lenses were barely distinguishable. Surprisingly, the moisture increase at a tension of 50 cm for these partially dried cores was nearly the same as for cores beginning at optimum in Figure 3. So, water moved to freezing fronts in the drier cores as easily as in more moist cores, but final water contents were substantially lower.

Water Absorption Plots

Moisture profiles and average ending moisture contents developed during ice lens growth were used as criteria for TBC performance in the preceding section. These represent ending values after several weeks of freezing and provide no information about what is happening during the run. This deficiency was overcome by continuously monitoring water absorption for each soil core using an off-line data acquisition system. Water absorption plots, similar to those shown in Figure 5, were machine generated for each run.

In the ice lens test, soil cores were first equilibrated with capillary moisture for about 1 week, while the bottom temperature was held near +3 C. Freezing was then initiated by cooling cores from the top and nucleating ice with liquid nitrogen. Ice nucleation was followed by abrupt exotherms 1 to 2 C high that lasted about 20 hours, during which moisture absorption increased markedly. The maximum flow rates

Table 1. Soil description and analysis.

State	Identifying Number	USDA Type or Texture	Mechanical Analyses Sand	AASHO Silt	Clay	LL	PL	PI	AASHO Classification
Michigan	11-B	Loam	49	31	20	31	22	9	A-4
	11-C	Clay loam	25	24	51	37	19	18	A-6
	13-C	Selkirk silty clay	9	34	57	57	24	33	A-7-6
	14-D	Selkirk silt loam	6	65	29	24	21	3	A-4
	14-E	Selkirk silt loam	5	55	40	28	18	10	A-4
Iowa	23-B	Silt loam	30	53	17	29	25	4	A-4
	23-D	Silt loam	8	81	11	—	—	—	A-4
West Virginia[a]	2	Upshur silty clay	2	27	71	62	22	40	A-7-6
	3	DeKalb sandy loam	44	25	21	17	17	N. P.	A-2-4
	5	Gilpin silt loam	14	32	54	47	27	20	A-7-6
	10	Berks silt loam	25	39	36	31	19	12	A-6

[a]Supplied by Lyle K. Moulton and Ray Martin, Civil Engineering Department, West Virginia University.

Figure 1. Cell for growing ice lenses in soil cores.

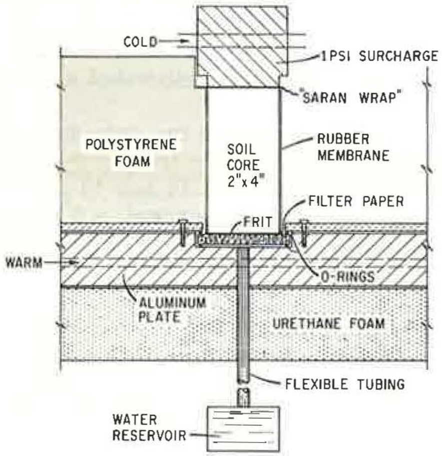


Figure 2. Moisture profiles for Iowa silt (23-B).

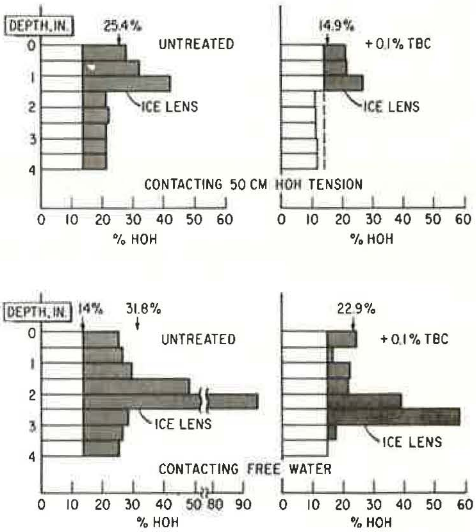


Figure 3. Average ending moisture contents for Iowa silt (23-B).

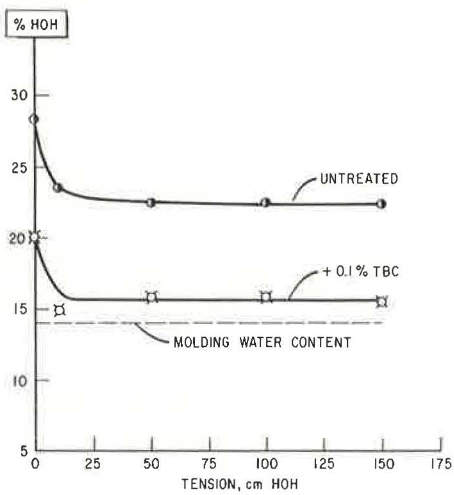
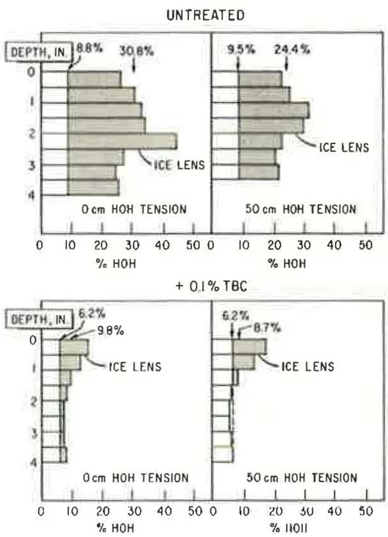


Figure 4. Moisture profiles for Iowa silt (23-D).



lasted from about 20 to 50 hours and then decreased with time, occasionally going to zero. The water absorption rates diminished with time because moisture was becoming depleted below the ice lens and because the ice lens was reaching equilibrium as described by Penner (28). In Figure 5, cumulative water flow at a tension of 100 cm is plotted for soil cores treated with TBC levels ranging from 0 to 0.1 percent. Cumulative total flow can be converted to percentage of water content increase as indicated by the right-hand axis in Figure 5. Roughly 400 grams of dry soil were contained in each core; therefore 4 cc of water absorption represent approximately 1 percent increase in moisture content.

Ice Lens Test Compared to Capillary Flow Test

Maximum water absorption rates during initial stages of ice lens growth were calculated from cumulative water plots similar to those shown in Figure 5. The values for soil 14-D are shown in Figure 6A. Water absorption ranged from 0.38 cc/hr in untreated samples to 0.12 cc/hr, one-third less, for samples containing 0.1 percent TBC. A core containing 0.01 percent TBC flowed at 0.18 cc/hr, roughly half the untreated rate. Average ending moisture contents for the same set of cores are shown in Figure 6B, showing essentially the same trend as the maximum flow rates.

The capillary flow test was run on soil 14-E because soil 14-D had been depleted. Flow rates through these 1-in. thick cores were determined with a 50-cc head differential; the higher reservoir was set at a tension of 25 cm and the lower at a tension of 75 cm. Flow rates decreased from 0.48 cc/hr for untreated samples to 0.04 cc/hr, a tenfold decrease, for all TBC concentrations between 0.01 and 0.1 percent.

The plots shown in Figure 6 strongly indicate that capillary water flow in this particular soil can be markedly decreased by using TBC concentrations as low as 0.01 percent, whereas field installations always have been constructed using about 0.1 percent TBC. It is interesting to note in Figure 6 that flow rates for untreated soil are nearly the same in both the ice lens and capillary flow tests, but that TBC decreased capillary flow much more than flow to growing ice lenses. The flows to ice lenses were roughly four times the capillary flow rates for TBC-treated samples. This relationship appears in all the soils tested, but is less pronounced, capillary flow normally being roughly half the flow to ice lenses for TBC-treated samples. The difference in Figure 6 can be attributed partly to the clay content of soil 14-E being higher than that of soil 14-D.

In general, water flowed faster through untreated soil 1 in. thick under a moisture tension gradient of 50 cm than through 2-in. thick soil to a growing ice lens; however, the reverse was true for TBC-treated samples. That is, water flowed roughly half as fast through 1 in. of soil under a tension gradient of 50 cm as through 2 in. of soil to a growing ice lens. This means that the ice lens test generated a driving force equivalent to a moisture tension gradient of about 200 cm in TBC-treated samples. In untreated samples, the driving force equivalent was below a moisture tension gradient of 25 cm. This further suggests desaturation was prominent in TBC-treated samples but not in untreated porous soils.

Similar data for the ice lens and capillary conductivity tests are shown for soils 23-D and 11-B in Figures 7 and 8. Both these soils respond well to TBC treatment. For soil 23-D, flows to ice lenses decreased from 0.9 cc/hr for untreated to 0.1 cc/hr, about tenfold, for all TBC levels between 0.01 and 0.15 percent. Capillary flow rates decreased from 1.7 cc/hr for untreated to about 0.05 cc/hr, a thirtyfold decrease, for all TBC levels over 0.025 percent. The more sandy soil 11-B responded similarly, but required about 0.05 percent TBC for optimum effectiveness.

Soils containing more than 50 percent clay characteristically do not respond well to TBC treatment. Figure 9 shows flow rates to ice lenses for soils 11-C and 13-C, which contained 51 percent and 57 percent clay respectively. Maximum water absorption rates during initial stages of ice lens growth were essentially unaffected by adding TBC because the flows for untreated soils were already quite low and limited ice lens formation. The curve for soil 14-D is included from Figure 6A as a reference to show how responsive soils appear on the same plot.

Figure 5. Water absorption rates for Michigan silt (14-D).

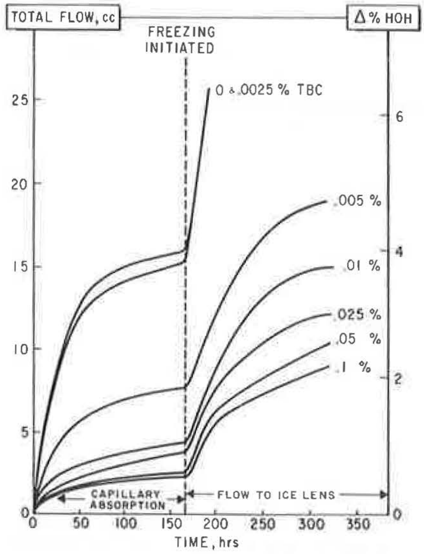


Figure 6. Moisture characteristics of Michigan silt (14-D).

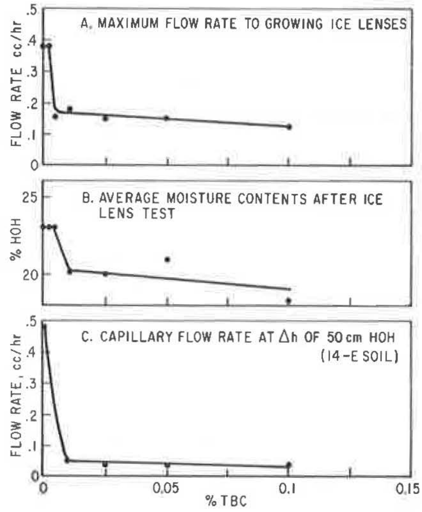


Figure 7. Moisture characteristics of Iowa silt (23-D).

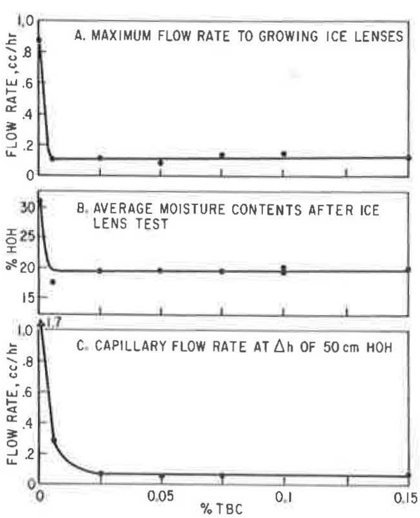
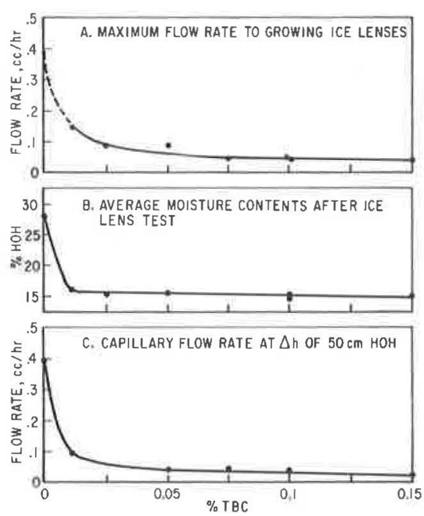


Figure 8. Moisture characteristics of Michigan loam (11-B).



Critical TBC Concentrations

Critical TBC concentrations determined by the ice lens test and the capillary flow test are significantly lower than those indicated by immersed, unconfined compressive strengths (Fig. 10). Immersed strengths have been used exclusively in the past to characterize critical chemical concentrations for field installations. Cores for three different soils, 14-D, 11-B, and 23-D, were immersed while at optimum moisture, and their strengths were measured (Fig. 10).

Two soils, 14-E and 11-B, require 0.1 percent TBC to achieve optimum immersed strength, whereas soil 23-D when immersed moist is near optimum with 0.05 percent TBC even though the strengths were relatively low. When air-dried prior to immersion, soil 23-D produces a strength curve represented by the dashed line in Figure 10, indicating 0.1 to 0.15 percent TBC is required for optimum performance. The discrepancy between critical concentrations indicated by the strength test, particularly after drying, compared to those from the flow tests suggests the strength test may overestimate chemical concentrations needed in field placement for adequate waterproofing. However, there are other questions regarding long-term permanence that must be considered, as well as the relevance of the flow tests to enduring field performance.

West Virginia Soils

Similar tests were run on ten soils from West Virginia. The data from four representative soils in that series are presented in Figure 11 and Table 2. In this case, the capillary flow test was used to predict which soils would respond to TBC treatment in the ice lens test. All four soils produced essentially no immersed strength when treated with TBC and would normally be considered untreatable. However, soils 3 and 10 responded reasonably well to TBC in the capillary flow test. Soils 2 and 5 essentially did not respond to TBC treatment because their clay contents are 71 percent and 54 percent respectively, which produces low untreated flow rates. Generally, more TBC was required to reduce capillary flow in West Virginia soils than in the Michigan and Iowa soils tested.

Average ending moisture contents for the West Virginia soils are given in Table 2. TBC at 0.1 percent decreased moisture contents by 9.2 percent and 19.3 percent for soils 3 and 10 respectively but only reduced moisture accumulation in soil 5 by 3.6 percent. It did not alter moisture in soil 2. These results fall in essentially the order predicted from the capillary flow rate plots in Figure 11. This suggests that a strong relationship exists between the two parameters and that the simple capillary flow test can be used as a major frost-susceptibility criterion for soils similar to those studied in this report.

DISCUSSION OF RESULTS

Chemicals classed broadly as soil waterproofing agents are currently believed to modify soil physical properties by roughly similar mechanisms. The major differences among waterproofing chemicals arise from degree of effect rather than from difference of effect. This can be inferred because chemical structures active as soil waterproofing agents all contain hydrophilic groups that adsorb on soil grains and hydrophobic groups that extend outward from grain surfaces (4). Consequently, TBC can be used as a model compound for studying the mechanism involved in limiting frost heave with soil waterproofing compounds.

TBC appears to limit ice lens formation in frost-susceptible soils primarily because capillary flow through unfrozen soil is reduced and because the tendency for unfrozen soils to absorb water is decreased. Treated soil cores absorb very little capillary water when exposed to controlled moisture tensions, but untreated specimens absorb water freely. Thus, untreated cores begin the freezing cycle at considerably higher water contents than do treated samples. As growing ice lenses consume water from unfrozen soil, additional water is freely supplied through highly frost-susceptible silty soils. But, TBC reduces flow to ice lenses enough to deplete water in the unfrozen

Figure 9. Comparison of maximum water absorption rates of moderately frost-susceptible soils (11-C and 13-D) and highly frost-susceptible soil (14-D).

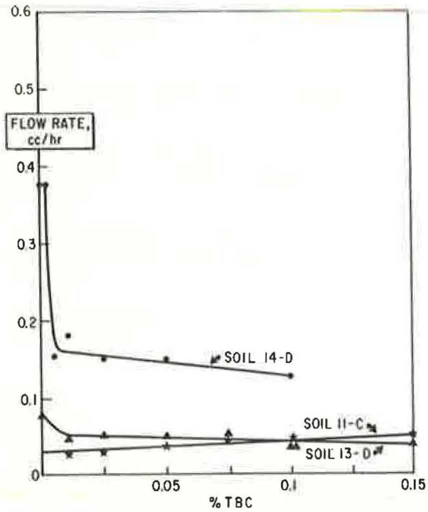


Figure 10. Immersed unconfined compressive strengths of three soils containing increasing levels of TBC.

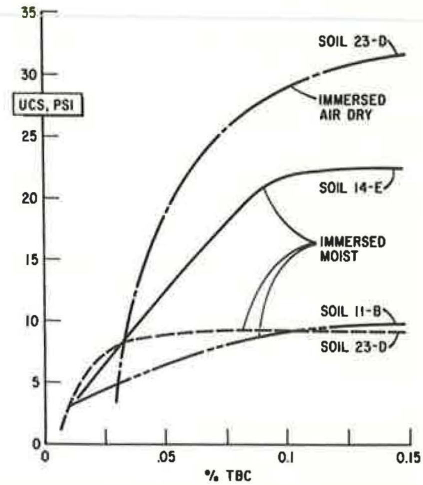


Figure 11. Capillary flow rate (at Δh of 50-cm HOH tension) for West Virginia soils.

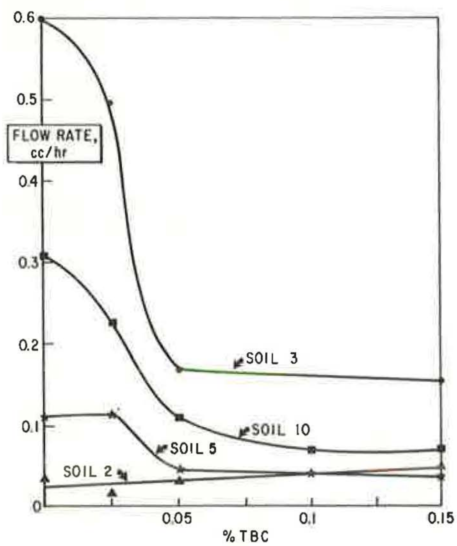


Table 2. Average moisture contents after ice lens test run at moisture tension of 50 cm.

Soil	Percentage of HOH After Freezing Test: Untreated	+0.1 Percent TBC	Decrease (percentage of HOH)
West Virginia 3	31.0	21.8	9.2
West Virginia 10	38.0	18.7	19.3
West Virginia 5	25.2	21.6	3.6
West Virginia 2	23.0	22.8	0.2

layer. In this study, flow to ice lenses was reduced threefold in one soil and tenfold in another. As a net effect, Iowa silt loam cores frozen 21 or more days contained about 7 to 10 percent more water in untreated samples than in treated samples. Final moisture contents for other responsive soils were 5, 13, and 19 percent higher in untreated samples. Reduced affinity for water is accomplished by using as little as 0.01 percent TBC in some soils.

Ice lens formation was increased significantly when cores contacted free water as contrasted to higher moisture tensions. However, tensions between 10 and 150 cm did not seem to alter extent of ice lens formation in Iowa silt loam. However, unreported data indicate moisture accumulation in other soils was more dependent on moisture tension, although differences were small. Apparently, the range of tensions considered in this study influenced the net driving force only slightly compared to the driving force induced by water moving from liquid to solid phase during ice lens formation. More careful experiments would be necessary to confirm this result and to test quantitative models previously proposed for calculating maximum frost-heave rates (30).

Temperature gradient also contributed in an inconsistent and apparently minor way to the net driving force during ice lens growth. This observation refutes data reported previously (3) in which temperature gradient was found to significantly alter water flow rates to growing ice lenses. More recent data suggest ice nucleation difficulties generated the earlier trend. Low temperature gradients produced water absorption rates equivalent to those from much higher gradients in earlier studies. As long as the temperature gradient supports nonlimiting heat flow, the contribution to water absorption should be small compared to the driving force generated by freezing liquid water supplied from unfrozen soil.

As discussed previously, hydrophobic chemicals change soil properties when soils are moist as well as when dry. The mechanism in dry soil is at least qualitatively understood (21), whereas that for moist soils is poorly understood (2). Lambe (25) demonstrated that waterproofing chemicals are excellent for decreasing heave rates after soils are dried, whereas the present paper shows newer chemicals limit ice lens growth in moist soils. Data presented in this paper also show that TBC reduces unsaturated moisture flow tenfold to thirtyfold in some porous soils and that all reductions in frost heave observed in this study can be attributed to reduced flow through unfrozen soil. The reduced capillary flow can in turn be attributed to disrupted water structure or perhaps to blocked pores in moist soils.

Even though the reduced capillary flow model appears to be an adequate explanation for how waterproofing chemicals reduce frost heave, other contributing factors may be discovered to be important by using different tests. Conceivably, heaving pressure could be altered by reducing the ice water interfacial energy. Also, the thickness of unfrozen water layers around mineral grains in frozen soil may be changed. Neither of these contributions could be assessed from the present studies.

Soils of varying frost susceptibility and type were included in this study to see how TBC influenced heave in a range of soils. Furthermore, the results from the ice lens, capillary flow, and immersed strength tests could be compared. TBC effectively treated all soils from the A-4 group, but the different tests identified different critical TBC levels. For soils from the A-4 classification, the flow test and the ice lens test indicated that 0.01 to 0.025 percent TBC minimized moisture flow. But, the immersed UCS test indicated that 0.05 to 0.1 percent TBC maximized strength in moist soils. For samples immersed after drying, 0.1 percent TBC is normally needed.

One A-6 soil from West Virginia containing 36 percent clay responded to TBC treatment as indicated by the capillary flow and ice lens tests (requiring 0.1 percent TBC), but air-dry cores disintegrated when immersed. Another A-6 soil from Michigan failed all tests regardless of TBC level because it contained more than 50 percent clay. An A-2-4 soil from West Virginia responded to treatment in the flow and ice lens tests but produced very low immersed strengths. Three soils in the A-7-6 classification did not respond to TBC treatment in any of the tests. Each contained more than 50 percent clay and produced low capillary flow rates when untreated.

Soils responding to TBC treatment as indicated by the hydraulic flow test are classed as SS or SSLS using a scheme proposed by Miller (26). In SS or SSLS soils, solid-solid contact between sand and silt grains dominates the soil matrix, and moisture flows primarily through capillary pores. Conversely, TBC increased hydraulic conductivity slightly in soils classed SLS, which contained more than 50 percent clay. In SLS soils, clay grains are separated by adsorbed moisture films, and moisture migrates primarily through the adsorbed films. This observation means that TBC and probably other soil waterproofing chemicals do not reduce flow through nonfrozen adsorbed water films at the freezing front. Rather, TBC reduces frost heave by disrupting flow through larger capillary pores.

The correlation between the hydraulic conductivity test and ice lens test strongly suggests that the flow test can be used to characterize the frost susceptibility of soils. The test is simple, fast, and dependable in comparison to most freezing tests. Torrence and Miller (30) developed a relationship between water flux and heave rate for conditions of nonlimiting heat flow that further suggests hydraulic conductivity should be used more extensively as a measure of frost susceptibility. It would be most interesting to compare hydraulic conductivity with the accelerated heaving-rate test recently proposed by Kaplar (24).

CONCLUSIONS

A model soil waterproofing compound, TBC, reduces frost heave in soils primarily by interfering with moisture movement through unfrozen soil. Moisture flow rates to growing ice lenses and capillary flow rates are both minimized in many soils by using 0.01 to 0.05 percent TBC. In contrast, immersed strengths are maximized by using 0.05 to 0.1 percent TBC (or higher optimum chemical concentration than indicated by moisture flow tests). Reduced frost heave in dry TBC-treated soils is easily understood because small hydrophobic pores with high apparent contact angles remain dry when exposed to water, thus reducing flow. In moist TBC-treated soils, reduced capillary flow may be caused by disrupted moisture films in capillaries or by reduced moisture film thickness, both of which reflect alteration of water structure.

Close correlation between frost heave and hydraulic conductivity has been reported by previous investigators and is strongly supported in this study. Therefore, hydraulic conductivity should be seriously considered as a major frost-susceptibility criterion. Soils in the A-4 classification produced high untreated hydraulic conductivities that were reduced threefold to thirtyfold by TBC treatment. Ice lens formation was similarly reduced but not to the same extent. Soils containing more than 50 percent clay (A-7-6 and one A-6 classification) produced low untreated hydraulic conductivity, had little tendency to grow ice lenses, and did not respond to TBC treatment.

REFERENCES

1. Brandt, G. H. Water Movement in Hydrophobic Soils. Proc. Symposium on Water-Repellent Soils, Univ. of California, Riverside, 1968.
2. Brandt, G. H. Soil Physical Properties Altered by Adsorbed Hydrophobic Materials. Proc. Symposium on Water-Repellent Soils, Univ. of California, Riverside, 1968.
3. Brandt, G. H. Chemical Regulation of Ice Lens Growth in Soils. Presented at Symposium on Freezing and Thawing Phenomena in Soils, American Soc. Agronomy Annual Meeting, New Orleans, 1968.
4. Bozer, K. B., Brandt, G. H., and Hemwall, J. B. Chemistry of Materials That Make Soils Hydrophobic. Proc. Symposium on Water-Repellent Soils, Univ. of California, Riverside, 1968.
5. DeBano, L. F., Osborn, J. F., Krammes, J. S., and Letey, J., Jr. Soil Wettability and Wetting Agents...Our Current Knowledge of the Problem. U. S. Forest Service Pacific Southwest Forest and Range Exp. Sta., U. S. Forest Service Res. Paper PSW-43, 1967.
6. Fink, D. H., and Myers, L. E. Synthetic Hydrophobic Soils for Harvesting Precipitation. Presented at Symposium on Nonwettable Soils, Univ. of California, Riverside, 1968.
7. Hemwall, J. B. The Adsorption of 4-Tert-Butylpyrocatechol by Soil Clay Minerals. Proc. Internat. Clay Conference, Stockholm, 1963.

8. Hemwall, J. B. Method for Improving Physical Properties of Clays and Clay-Containing Soils and Compositions Resulting Therefrom, Including Quaternary Ammonium Compounds. U. S. Patent 3,073,064, 1963.
9. Hemwall, J. B. Method for Improving Physical Properties of Clays and Clay-Containing Soils and Compositions Resulting Thereform. U. S. Patent 3,082,112, 1963.
10. Hemwall, J. B. Method for Improving Physical Properties of Clays and Clay-Containing Soils and Compositions Resulting Therefrom. U. S. Patent 3,082,113, 1963.
11. Hemwall, J. B. Method for Improving Physical Properties of Clays and Clay-Containing Soils and Compositions Resulting Therefrom. U. S. Patent 3,084,058, 1963.
12. Hemwall, J. B. Method for Improving Physical Properties of Clays and Clay-Containing Soils and Compositions Resulting Thereform. U. S. Patent 3,132,960, 1964.
13. Hemwall, J. B. Method for Imparting Improved Properties to Clays and Clay-Containing Materials by Use of 2-Aminophenols and Compositions Resulting Thereby. U. S. Patent 3,148,995, 1964.
14. Hemwall, J. B. Catechol Compounds in Improving Clays and Clay-Containing Materials. U. S. Patent 3,148,997, 1964.
15. Hemwall, J. B. Use of Methylene Polyphenols for Improving Physical Properties of Clays and Clay-Containing Materials and Compositions Resulting Therefrom. U. S. Patent 3,132,958, 1964.
16. Hemwall, J. B. Method for Improving Physical Properties of Clays and Clay-Containing Materials and Composition Resulting Therefrom. U. S. Patent 3,151,998, 1964.
17. Hemwall, J. B. Use of 6,6'-Alkylidenebis(benzoxazines) for Improving Physical Properties of Clays and Clay-Containing Soils and Compositions Resulting Therefrom. U. S. Patent 3,124,472, 1964.
18. Hemwall, J. B. Use of 8,8'-Methylenebis(benzoxazines) for Improving Physical Properties of Clays and Clay-Containing Soils and Compositions Resulting Therefrom. U. S. Patent 3,124,473, 1964.
19. Hemwall, J. B. Method for Improving Physical Properties of Clays and Clay-Containing Soils and Compositions Resulting Therefrom. U. S. Patent 3,126,290, 1964.
20. Hemwall, J. B. Use of Thiobisphenols for Improving Physical Properties of Clays and Clay-Containing Soils and Compositions Resulting Therefrom. U. S. Patent 3,132,957, 1964.
21. Hemwall, J. B., and Bozer, K. B. Moisture and Strength Relationships of Soils as Affected by 4-Tert-Butylpyrocatechol. Soil Science, Vol. 98, 1964, pp. 235-243.
22. Hemwall, J. B., Davidson, D. T., and Scott, H. H. Stabilization of Soils With 4-Tert-Butylpyrocatechol, HRB Bull. 357, 1962, pp. 1-11.
23. Jumikis, A. R. Thermal Soil Mechanics. Rutgers Univ. Press, 1966.
24. Kaplar, C. W. Experiments to Simplify Frost Susceptibility Testing of Soils. Cold Regions Research and Engineering Laboratory Tech. Rept. 223, 1971.
25. Lambe, W. T. Modification of Frost Heaving of Soils With Additives. HRB Bull. 135, 1956, pp. 1-23.
26. Miller, R. D. Phase Equilibria in Soil Freezing, Permafrost: International Conference Proceedings (1963). National Academy of Sciences, National Research Council, Publ. No. 1,287, Washington, D. C., 1965, pp. 193-197.
27. Nielsen, D. R., and Bigger, J. W. Measuring Capillary Conductivity. Soil Science, Vol. 92, 1961, pp. 192-193.
28. Penner, E. Frost Heaving in Soils, Permafrost: International Conference Proceedings (1963). National Academy of Sciences, National Research Council, Publ. No. 1,287, Washington, D. C., 1965, pp. 197-202.
29. Sharma, M. L., and Uehara, G. Influence of Soil Structure on Water Relations in Low Humic Latosols: II. Water Movement. Proc. Soil Science Soc. of America, Vol. 32, 1968, pp. 770-774.

30. Torrance, J. K., and Miller, R. D. Hydraulic Conductivity as a Limitation to the Rate of Frost Heaving. Presented at Symposium on Freezing and Thawing Phenomena in Soils, American Soc. of Agronomy Annual Meeting, New Orleans, 1968.

DISCUSSION

Lyle K. Moulton, West Virginia University, and Ray E. Martin, Schnabel Engineering

Dr. Brandt is to be commended for his fine paper dealing with the use of soil waterproofing chemicals to reduce water accumulation and frost heaving in soils. The rather innovative and sophisticated laboratory testing techniques and data acquisition systems described by the author are particularly laudable.

In general, the writers agree with the author's objectives and some of his conclusions. There is a very real need "to quantify frost heave as influenced by drainage, temperature gradient, chemical concentration, and soil type." More important, however, from the writers' viewpoint, is the author's implication that the needs of his study were dictated by the fact that "limiting conditions for adequate chemical performance in the field needed to be defined." The writers are not convinced that the results of tests reported by the author, or his suggestion that hydraulic conductivity be "considered as a major frost-susceptibility criterion," entirely satisfy the latter objective.

The purpose of TBC, or for that matter any waterproofing chemical, is to reduce moisture absorption in the field, to retain as much as possible the as-compacted density and strength of the subgrade, and to limit the detrimental effects of frost action, particularly with respect to frost heave and the associated loss of subgrade support during spring thaw. Although the hydraulic conductivity of the subgrade soil and the resultant changes in subgrade moisture content are a very real part of the varied mechanisms associated with the performance of pavements, it appears to the writers that some measure of soil strength and its influence on pavement design might be a more realistic way to evaluate the effectiveness of a waterproofing chemical such as TBC than some of the indirect tests employed by the author. Accordingly, in a series of tests conducted recently at West Virginia University, the writers attempted to evaluate the effectiveness of TBC in terms of its ability to economically reduce the thickness of the required pavement structure for both frost and no-frost conditions (31).

Ten typical West Virginia subgrade soils were selected for study, utilizing the pavement design procedure prescribed by the West Virginia Department of Highways (32). This method is an adaptation of the California procedure originally developed by Hveem (33) and modified by the results of the AASHO Road Test (34). Briefly, this pavement design procedure evaluates the adequacy of the subgrade by using the following steps: (a) preparation of test specimens by kneading compaction, (b) determination of the consolidation or drainage characteristics of these specimens by an exudation pressure test, (c) determination of the swell characteristics of the compacted samples by an expansion pressure test, and (d) determination of the undrained strength of the soil in terms of resistance value as defined by the Stabilometer test. Soils treated with 0.05 percent and 0.10 percent TBC as well as untreated soils were evaluated by this procedure.

For the TBC-treated soils, it was found that, in general, both the exudation pressures and swell pressures were lower than for the untreated soils. For most of the soils, the TBC treatment resulted in higher Stabilometer resistance values. The overall result was that, for no-frost conditions, the TBC treatment resulted in a net reduction in the thickness of the required pavement structure for eight of the ten soils tested. At the 0.05 percent treatment level, the reductions in the non-frost-susceptible subbase ranged from 0 to 2 in., whereas at the 0.10 percent treatment level, the reductions ranged from 1 to 6 in. For the eight soils, where TBC treatment of the subgrade would have led to reductions in the design pavement thickness, only one soil displayed optimization of the TBC treatment at the 0.05 percent treatment level. In fact, there were distinct indications that treatment levels higher than 0.1 percent might have been required to produce optimum reductions in required pavement thickness. These results differ significantly from the results that would have been obtained by using hydraulic conductivity as a basis for optimization of the TBC treatment level.

Although the methods used in the West Virginia University study did not permit direct laboratory evaluation of the ability of TBC to limit ice lens development, frost heave, and loss of subgrade support during spring thaw, these factors were considered in terms of the procedure developed by Moulton and Schaub (35). This method of evaluating the effect of TBC on the design of pavements for frost conditions is considered to be conservative, and a more direct laboratory procedure has been proposed by Martin (31). Nevertheless, the results obtained were similar to those for the no-frost condition; i.e., very definite reductions in the required thicknesses of the pavement structures were observed for most of the soils studied. However, these reductions were generally less than observed for the no-frost condition at the same treatment level.

Based on these results, the writers concluded that TBC showed considerable promise as a waterproofing soil stabilizer for use with West Virginia soils. However, a cost comparison showed that, at current prices, the use of TBC for the waterproofing of subgrade soils in West Virginia could not be justified from an economic standpoint. This is not meant to imply that TBC treatment would not be suitable or economical for other soils in other areas. In fact, it is recommended rather strongly that each individual soil be evaluated to determine the actual concentration of TBC required for effective treatment. However, the writers do not feel that hydraulic conductivity by itself is entirely adequate to define the TBC treatment levels necessary to ensure optimum pavement design and performance.

References

31. Martin, R. E. Evaluation of the Effectiveness of TURBEC Soil Stabilizer for Use With West Virginia Soils by the Stabilometer Method. West Virginia University, PhD dissertation, 1972.
32. West Virginia State Road Commission. West Virginia Pavement Design Manual. February 1966.
33. Hveem, F. N., and Carmany, R. M. The Factors Underlying the Rational Design of Pavement. HRB Proc., Vol. 28, 1948, pp. 101-136.
34. Hveem, F. N., and Sherman, R. M. Thickness of Flexible Pavements by the California Formula Compared to AASHO Road Test Data. Highway Research Record 13, 1963, pp. 142-166.
35. Moulton, L. K., and Schaub, J. H. A Rational Approach to the Design of Flexible Pavements to Resist the Detrimental Effects of Frost Action. Highway Research Record 276, 1969, pp. 25-38.

AUTHOR'S CLOSURE

The largest single deterrent to advancements in soil stabilization is the lack of criteria, based on laboratory tests, that can be used to predict field performance. Consequently, I agree with Moulton and Martin that the ice lens test and the hydraulic flow test are inadequate to define all the "limiting conditions for adequate chemical performance in the field." Rather, the need to define limiting conditions led to measuring ice lens growth and hydraulic conductivity in an attempt to understand how and under what conditions waterproofing chemicals limit water migration to freezing fronts in soils. Certainly, the tests cannot be used as direct criteria for a design procedure based on strength-retention parameters. However, they can be used indirectly to help define the conditions under which strength loss during thaw will be minimized by additives.

The design procedure referred to by Moulton and Martin offers considerable promise as a tool for evaluating soil stabilizing chemicals. Design cross sections are calculated from direct laboratory tests, and costs for constructing various cross sections can be compared to determine whether a proposed soil stabilization treatment is competitive with conventional construction practice. Numerous cross-section alternatives can be evaluated by the model; then cross sections that are both technically and economically optimum can be placed into long-term field tests to verify the design model as applied to chemically stabilized soil layers. However, before this can be accomplished, improvements are needed in predicting strength loss during spring thaw after frost has penetrated subgrade soils, as indicated by the fact that Martin (31) has proposed a direct procedure to evaluate this very important parameter.

Hydraulic flow rates are shown in Figure 11 for only four of the ten soils from West Virginia that have been characterized by Moulton and Martin and by the author. Actually, six of the ten soils produced lower hydraulic flow rates when treated with 0.1 percent TBC than when treated with 0.05 percent chemical, two produced minimal flow at the 0.05 percent treatment level, and the remaining two soils did not respond to treatment. This agrees closely with the minimal treatment levels described by Moulton and Martin. However, data for soils from other states in the original paper demonstrate that different minimum concentrations are indicated by each measurable parameter: flow rate to growing ice lenses, moisture contents after ice lens formation, capillary flow rate, immersed strength of moist cores, and immersed strength of air-dried cores. We have yet to determine which test produces the minimum concentration that can be most reliably translated to expected field performance. Perhaps the procedures advocated by Moulton and Martin can help resolve this problem.