Phenomenon and Mechanism of Frost Heaving

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This paper presents a mechanistic explanation of frost action in soils, based on the hypothesis that liquid films existing between particles and an ice lens are the focal centers of energy for the heaving (work) process. Heaving, upon freezing, is not a unique property of soil particles and water; lensing and segregation occur with other powdered materials and other liquids. An explanation of the development of "suction" forces in unfrozen liquid below the ice lens is presented and experimental data are provided for two cases—a closed system and an open system. The effect of heat extraction rate and freezing penetration rate on rate of heaving is discussed. Experimental laboratory data indicate two critical rates of freezing: (a) maximum heave rate and (b) minimal heave rate equal to volume expansion of in situ (void) water.

Heave rate and work of heaving and their dependence on free energy generation during freezing are discussed in general terms. Typical experimental data are presented illustrating the reduction in heave rate with increased external (and internal) resistance. The role of soil structure in frost susceptibility is discussed. Changes in frost heaving rates can be effected by addition or removal of either, or both, the coarse aggregate or soil fines. Suggestions are offered for approaches to soil modification to reduce heaving.

This paper presents an easily understandable mechanistic description of the frost heaving phenomenon and the simultaneous presence of pressure and subpressure in the system, and points out the important soil parameters involved in frost heaving.

•EARLY INVESTIGATORS demonstrated conclusively that soil heaving is caused by migration of water within the soil to the freezing front, forming an ice lens (2, 18). The ice lens grows parallel to heat flow, unless restrained, and heaving occurs in the direction of least resistance. A precise and complete explanation of this basic phenomenon is still not available, although Taber (18) was sufficiently farsighted to postulate that a thin film of liquid separated the ice phase from the soil grains and that movement of water to feed the ice lens above the soil grains was through these thin films. Beskow (2) also believed that such a thin film was an important factor in the heaving process.

Experimental work at the U. S. Army Cold Regions Research and Engineering Laboratory (USACRREL) by Corte (4) demonstrated convincingly that a thin liquid film must separate the ice layer and soil particles and contain the force mechanism tending to keep them apart. Corte's experiment consisted of freezing water from the bottom upward in a large wide-mouthed jar as shown in Figure 1. After partial freezing upward, Corte sprinkled into the water above the ice several sizes of small soil grains, which came to rest over the ice. As freezing of the water was slowly continued upward, he observed that some of the soil grains moved up with the ice front (direction of lease resistance), while others were engulfed by the ice. Various rates of freezing showed that different sizes of particles were either thrust upward or were engulfed. The fact that some particles were moved upward for any distance indicates that they had to be supported by a liquid-like film (not visible or measurable in the experiment); otherwise the water would freeze around them and they would not move. To maintain a film beneath the particle requires that new water enter the film to replace water

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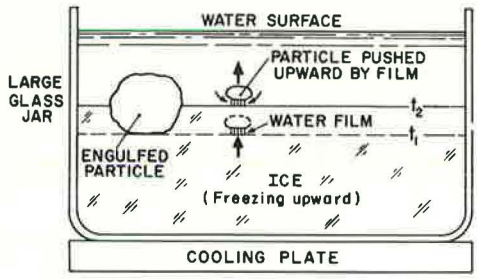

Figure 1. Corte's experiment.

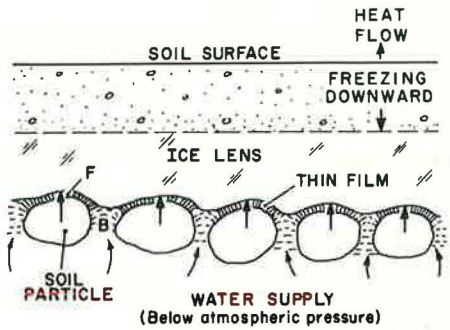

Figure 2. Active thin films separating ice and fine particles.

molecules transformed into ice. If shape or weight of the particle slows the diffusion or replacement process, the particle will be engulfed by the forming ice. In Corte's experiment, particle sizes that were engulfed under one rate of freezing were observed to migrate when the freezing rate was reduced, thus permitting more time for new water molecules to resupply the film.

Similar experiments involving matrix liquids of water, salol, thymol, and orthoterphenyl and using particles of graphite, magnesium oxide, silt, silicon, tin, diamond, nickel, zinc, iron oxide, and silver iodide have been reported (21). Particle rejection by the frozen phase of various liquids used was observed, and velocity rates of particle movement were measured in these studies. Hoekstra and Miller (6) also report exclusion of spherical glass beads and rods from an upward advancing ice front.

FROST HEAVING MECHANISM

With the functional concept of the thin film as a force mechanism as demonstrated by Corte (4) and Uhlman (21), we can now visualize the heaving mechanism in a mass of fine soil particles, when frozen from the top down. Figure 2 shows a section of a downward freezing soil mass in which an ice lens is growing. For ice segregation to occur, a quasi-liquid layer, as indicated at position F in Figure 2, must exist and provide the driving force. This specific layer between soil and ice is called the active film layer.

The summation of all the individual active layer forces acting in concert during freezing provide the total lifting force on the frozen material above. This is shown in Figure 3 for a cross section of soil. The more fine particles in the plane of freezing the greater the heave force will be.

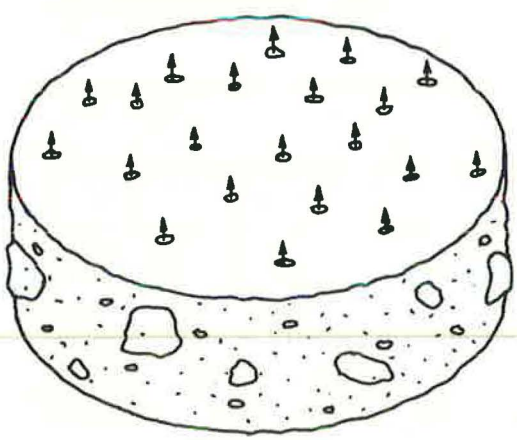

Figure 3. Hypothetical section across cylindrical soil specimen depicting upward thrust of active film layers immediately below ice lens.

The molecular layers of water in contact with the ice possess a high degree of polar orientation with the ice lattice and thus have a fairly rigid and ordered structure. The adsorbed water on the soil particle is likewise bound by strong adsorption forces, as evidenced by heat of wetting, and also possesses a high degree of structural rigidity different from layers adsorbed on the ice.

It can be assumed that as a result of freezing within the active film layer a water molecule undergoes a physical adjustment of its position in order to fit properly into the ice crystal lattice. In the

process, the force balance is disturbed and a rearrangement of the remaining water molecules occurs to restore equilibrium, and water molecules from the void water are attracted to satisfy the unbalance. Less energy is required to attract and freeze the outside molecules than to remove a molecule from the adsorbed layer on particle. Investigations have shown that the adsorbed water molecules at the surface of very fine particles can be exchanged with other water molecules relatively rapidly, because their diffusion rate is high if travel paths are short (15).

The demand for replacement molecules into the active film layer is thus governed by the volume rate of phase transition within the layer. Of course, additional water molecules outside the active layer are also frozen onto the ice lens, as at point B in Figure 2. If flow to the freezing front (including active layers) from adjacent areas equals the loss of water molecules to ice, then a substantially stationary freezing front can be maintained and a thick lens will develop. If the freezing temperature gradient is such that the freezing of water at point B is greater than at point F, then the ice at B will take a convex shape as dictated by the void space between particles. In the process, the active film area between particle and ice above becomes larger, but at the same time the replacement flow path to the apex is greater and flow diminishes, and the convex ice finger will either penetrate through the narrow void or a new ice nucleus will form below, engulfing the soil particles in a continuing heaving process.

Heaving may be produced by the growth of a clean ice lens or during frost penetration, wherein many particles are engulfed, individually or in clusters, to give a homogeneous or heterogeneous appearance, as the circumstances may dictate. Heaving is not necessarily accompanied by clearly distinguishable ice lenses.

The width, thickness, and surface characteristics of the particle are important for water supply. It is also important that a particle be small enough to have either an upper or lower surface within the plane of freezing. For uniform fine-grained soils the plane of freezing will be relatively uniform on a macroscale but undulating or irregular on a microscale, compensating for slight differences in composition compaction. The maximum heaving action will occur when the area of active film layers is maximum in a freezing front system. Larger particles lying across the freezing front do not contribute to the heaving activity and, in fact, inhibit it.

In this paper we are not concerned with the origins of the energy or with thermodynamic formulations of ice-film-particle relationships. This is for the soil physicists and physical chemists to formulate and debate. We only wish to emphasize the confirming evidence, available from the particle migration studies of Corte (4), Uhlman et al (21), and others, that a force mechanism exists in the quasi-liquid active layer separating the particle from the solidified liquid. This force mechanism can do work, and work requires expenditure of energy. Any explanation or application to engineering problems requiring reliable prediction and control must eventually consider quantitatively the thermodynamics of the whole system, including particle sizes, shapes, and distribution; solid (ice and water particle)-liquid interrelationships; simultaneous flow of heat and water; and thermal rate processes. A good mechanistic explanation of the frost heaving phenomenon has been prepared by Wissa and Martin (22).

PARTICLE FINES AND LIQUIDS IN LENS SEGREGATION

It has been established that soil fines in the presence of free water provide the necessary conditions for ice segregation. Recent studies and earlier data reveal that ice segregation is not restricted only to soils; ice segregation may occur within various materials consisting of a mass of discrete fine particles. These particles may be organic, metallic, or a combination of powder-fine minerals. Taber (18) demonstrated the occurrence of ice segregation in precipitated barium sulphate, lithopane, and Kadox (ZnO), with average particle diameters of 2, ½, and ¼ microns respectively.

Water is an essential ingredient for ice segregation during freezing in nature. However, water is not a necessary ingredient. Any wetting liquid that crystallizes upon a phase change during cooling and has a definable freezing point may provide active film forces. Taber (18) recorded heaving and lensing with nitrobenzene and with benzene, as did Kaplar (11) in laboratory tests (Fig. 4). It should be noted that nitro-

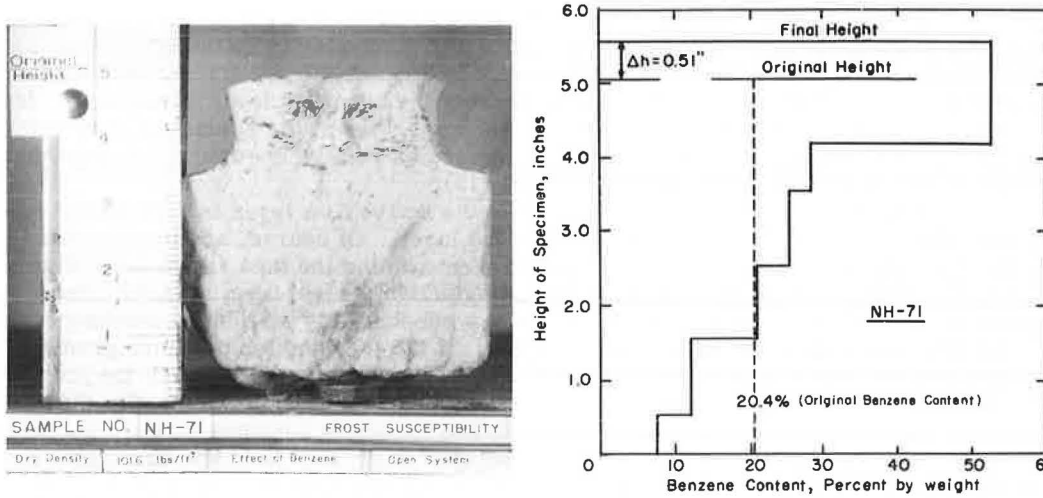

Figure 4. Left: New Hampshire silt after freezing showing lenses of benzene. (Corners show effect of drying and flaking off.) Right: Benzene distribution in specimen after freezing (11).

benzene and benzene contract upon freezing, and hence development of pressure within the active film layer cannot be merely attributed to volume expansion on phase change.

Recent studies (17) report heaving and lens formation in a powder of silica smoke, SiO_2, in diatomaceous earth, and in Linde alpha alumina powder, Al_2O_3. With Al_2O_3, three different liquids were used: nitrobenzene, o-chloroaniline, and formamide; segregated lenses were reported to have formed upon unidirectional freezing of these mixtures. Further experimentation using carbon black, pure magnesium oxide, and 600-mesh silicon carbide with water as a fluid also produced ice segregation upon freezing. The particular migration studies by Uhlman et al (21, p. 3) with several organic liquids support the universal nature of the segregation by freezing phenomenon.

SUCTION OR SUBPRESSURES DEVELOPED IN SOIL WATER DURING FREEZING

To many people the most puzzling phenomenon occurring in frost-susceptible soils is the seemingly mutually contradictory phenomena of the simultaneous existence of heaving pressure and the soil water subpressure (tension) during freezing. The explanation presented in this paper is based on the assumption that the primary heaving force emanates from the thin films separating fine particles and ice. Through this film is transmitted the intergranular effective stress on the soil particle system. When heaving is taking place the thin film forces act as miniature hydraulic jacks. In lifting the frozen soil slab upward, a suction is developed in the liquid between jacks causing moisture to flow in response to the pressure gradient created. This is analogous to a suction-type water pump where external air pressure provides the motive force. Pump delivery will depend on the pumping rate (energy supplied), the suction head, and the size of the supply pipe. In soil the supply of water for ice segregation will also depend on the distance to free water (equivalent to the suction head), the size and number of water passages, the rate of active film water frozen and replenished (jacking rate), and the number, size, and location of released air bubbles. The active layers need to pull in only a few molecules to replenish those lost to the ice phase to maintain the jacking action.

If the permeability of the soil is such that water cannot flow up fast enough to fill the demand, then several things are likely to occur. As water molecules are drawn into the active layer from adjacent voids (a) a tension (subpressure) will develop in the void water; (b) air or gas vapor bubbles will emerge from the solution, either from the pores

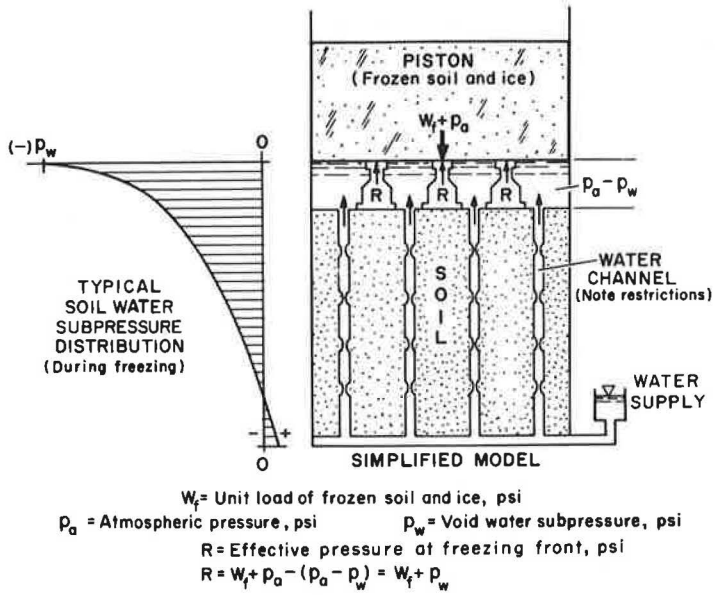

Figure 5. Simplified model demonstrating frost heave jacking and resultant void water subpressure.

on a rough particle surface or in voids between particles and thus further impede flow; and (c) freezing will penetrate deeper into the specimen. The closely packed vertical striations of these numerous extremely fine bubbles are nearly always seen in ice lenses, giving them a threadlike appearance.

Because of strong attraction for water molecules at the ice front, many highly impervious clayey soils undergo desiccation for a short distance below the freezing zone, and vertical shrinkage cracks may occur with accompanying consolidation. It has been stated that fat clays are not frost susceptible, Of course, this is not true; they are very frost susceptible, but their imperviousness restricts heaving. Nevertheless, thaw-weakening can be substantial.

A simplified model of a freezing soil system, the jacking action, and the development of void water subpressure are shown in Figure 5. It is not intended to imply with this model that the greatest subpressure that can be developed in the soil system is limited to atmospheric pressure. This is not so. The subpressure potential of the soil-water-gas films can be considerably greater as indicated by the theory of capillarity.

SUBPRESSURE MEASUREMENTS BENEATH ICE LENSES

Porous ceramic tensiometers attached to either mercury or water manometers were inserted into specimens of New Hampshire silt to measure the void water subpressures developed during freezing. Figure 6 presents the results of tests of a 12-in. high specimen slowly frozen downward in an open system. The readings show that a persistent subpressure of about 8 cm of mercury (Hg) was maintained in the specimen below the freezing front during freezing and heaving.

Figure 7 shows the subpressure developed at the base of a 6-in. high silt specimen slowly frozen from the top downward in a closed system test, i.e., no outside water available. The specimen started out with a small subpressure of 20 cm of Hg because it was not fully saturated. Freezing caused the subpressure to increase at the base as the water was withdrawn to the freezing front. A subpressure of 68 cm of Hg was measured before the mercury column separated. These results show the strong attraction for water molecules at the active film layers when freezing is taking place.

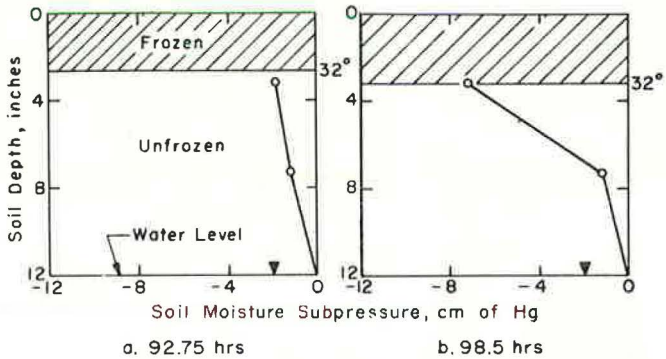

Figure 6. Soil moisture subpressure measurements in New Hampshire silt while freezing in open system.

EFFECT OF COOLING RATE ON HEAVE RATE

Studies by Penner (16) and by Kaplar (12) show that the heave rate is influenced by the cooling rate. In Arctic Construction and Frost Effects Laboratory (ACFEL) frost-susceptibility evaluation tests (10, 14), a low freezing rate of ¼ in. per day was used to simulate natural freezing. This method for laboratory freezing tests may have contributed to the wide range of heave rate results obtained for the same and similar soils in different test runs.

In view of recent heave rate data obtained with faster cooling rates, it is now believed that previous strict adherence in maintaining a low freezing rate was self-defeating if water supply to freezing front was impeded by released air inclusions or if specimen adfroze to cylinder walls. Any restraint of heaving normally results in a more rapid freezing penetration rate because of less latent heat release at the freezing front. The increased penetration rate, when observed by the operator, was corrected (reduced) by raising the air temperature in the freezing cabinet, thus further decreasing the heat extraction rate and consequently the heave rate. The use of a constant freezing temperature (12) appears to be a more reliable and repeatable procedure than the controlled rate of temperature penetration method previously used. Figure 11 in Kaplar's paper (12, p. 57) shows the effect of various rates of heat extraction, as controlled by lower surface temperatures, on several different types of soils.

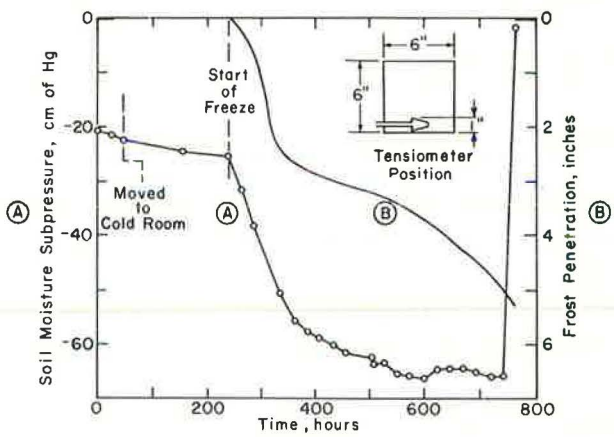

Figure 7. Soil moisture subpressure measurements in New Hampshire silt during freezing in closed system.

EFFECT OF FROST PENETRATION RATE ON HEAVE RATE

Because of the practical difficulties in maintaining a uniform slow rate (¼ in. per day) of freezing in laboratory frost studies for the different soils, an analysis of the actual and variable freezing rates obtained indicated that heaving rate was directly proportional to the freezing or heat extraction rate and not independent of it, as Beskow (2) stated. These observations led to a group of experiments on a "dirty" gravelly sand (Hutchinson pit) wherein the rates of frost penetration were varied up to 8 in. per day. One specimen was frozen at the extremely rapid rate of 18 in. per day. All specimens were in 6-in. high (inside-tapered) containers, open system, and prepared in accordance with adopted procedures (12). The test results are shown in Figure 8. The data indicate that the heave rate for the soil and the system used increases with increase in frost penetration rate to some maximum value and then begins to decrease (shown by extrapolated dashed curve) until the heave rate curve intersects the theoretical void (in situ) water expansion curve and becomes coincidental with it.

The heave rate measured at the 18-in. per day penetration rate fell very close to the void volume expansion curve. It thus appears that for laboratory specimens there are two critical rates of frost penetration:

1. $H_{R(max)}$, maximum heave rate, and
2. $H_{R(v)}$, heave rate beyond the maximum where ice segregation is reduced to practically zero and the heave rate is due solely to volume expansion during phase change.

These observations pertain to a specific 6-in. high soil frozen in the laboratory. Similar relationships would hold for other soils of equal height.

Based on these observations, it is deduced that soil water subpressures would exist beneath the ice front for all rates of freezing up to the second critical rate, $H_{R(v)}$, beyond which a positive pressure (in saturated case) equivalent to the total unit reaction resistance developed if in situ void water freezes before it can leave the void space.

Although these data are limited, the results indicate that laboratory freezing rates may be as high as 7 to 8 in. a day in similar base course soils and still produce useful heave rate data for comparative evaluation of frost susceptibility. At a freezing rate of 6 in. per day, test results could be available in 24 hours for 6-in. high test specimens.

HEAVE PRESSURE AND WORK OF HEAVING

The existence of strong soil heaving forces during freezing has been well demonstrated in nature by deformations of frozen ground; cracks in pavements; heaving of foundations of structures; and movement of retaining walls, posts, and utility poles.

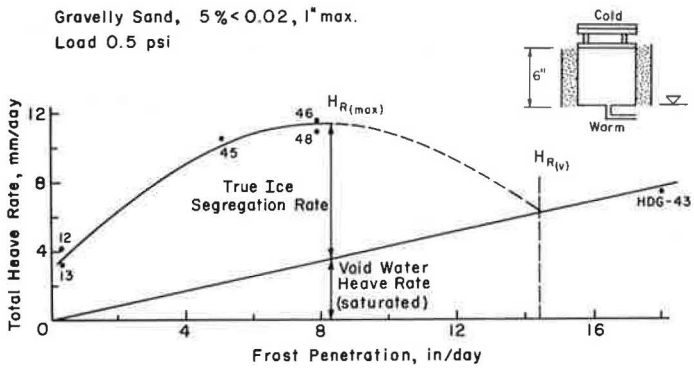

Figure 8. Heave rate vs rate of frost penetration.

Measurements have been made in the laboratory to determine the magnitude of this force in various soils (5, 9, 17). Large freezing pressures have been reported for the fine-grained soils.

In the heaving process it is obvious that work is being performed in lifting a load above the freezing front and in raising water up to the freezing front. Work requires the expenditure of energy. If the active liquid layer concept is correct and the thin films provide the primary lifting force, then the energy for doing work must originate within the thin films (8, 19, 20, 21).

Studies at ACFEL (14) and field observations (1) have demonstrated that a load on a frost-susceptible soil reduces the heaving rate and the total heave. A simple law of mechanics states that the amount of work is directly related to the energy expended, i.e.,

$$\text{Energy Expended, } E = \text{Work Performed} = \text{Resistance} \times \text{Distance} = P \times h$$

For a time rate process, the relationship becomes

$$\dot{E} = P \times \dot{h}$$

where $\dot{h}$ is the heaving rate and $\dot{E}$ is the free energy generation rate activated during freezing within the active film layers. It accounts for work done in the heaving process. The rate of heaving in a given soil has been observed to increase with increased heat extraction rate across the freezing front (12, 16), at least up to some limiting value of heat extraction rate. Use of this free energy to accomplish work depends on the availability of water to the active layer zone. Without water, work of heaving cannot occur, and the available energy is probably used to detach and freeze molecules of highly adsorbed water on particle surfaces. The amount of available usable work energy is believed to be a function of the size of the active film area (governed by particle diameter and surface characteristics) and also of the film thickness (separation between ice and particle surfaces). The layer thickness may be affected by several factors such as overburden load, rate of freezing within the layer, and difficulty or ease of obtaining water.

The total load, P_L, above the freezing plane that heaving forces must lift in laboratory experiments (and similarly in the field) consists of four components:

1. W_L, external surcharge load;
2. W_f, weight of frozen soil above freezing front;
3. S_p, void subpressure during freezing; and
4. F, internal frictional resistance to displacement, either at container walls or embedded material within the soil, expressed as an equivalent surface load.

Thus the total work energy expended in the heaving process may be expressed as

$$\dot{E} = P_L \times \dot{h} + \dot{W}$$

where $\dot{W} = \dot{h}\, P_W$ and is the work rate in lifting water, and P_W is a function of the soil water content and depth to water table.

Thus

$$\dot{E} = \dot{h}\,(P_L + P_W)\frac{1}{K} = \dot{h}\,(P)\,\frac{1}{K}$$

The above expression gives the equation of a rectangular hyperbola, where $K\dot{E}$ is a constant for particular soil and boundary conditions, and $\dot{h}$ and P are the rectangular variables.

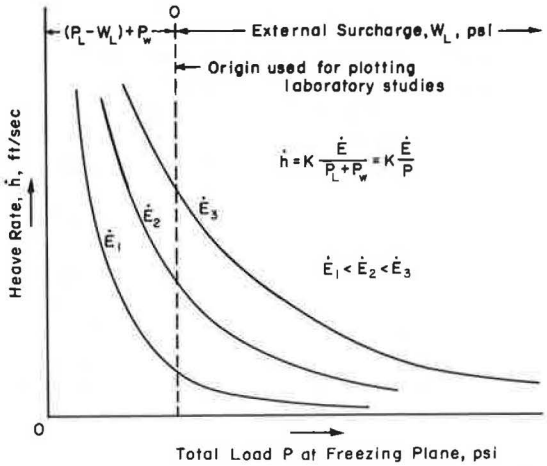

Figure 9. Theoretical curves illustrating relationship between heave rate and load resistance for different energy generation rates at freezing front.

For the range of work-energy generation rates, $\dot{E}$, capable of being developed at the freezing front, a family of curves can be drawn to represent the simplified work-energy relationships (Fig. 9).

Not all of the load or resistance factors mentioned are precisely known or have been measured in freezing tests. Only $\dot{h}$ and W_L are accuretely known; W_f can be closely estimated. Very little is known about the magnitude of subpressure, SP, for various soils under various conditions of temperature and other boundary conditions, and of the factor F.

An examination of the basic work equation, $E = P \times h$ where $P > 0$, explains why high unit pressures can be measured in a test situation where heaving is restrained. For a given quantity of work energy, E, P will become very large if h is negligible. However, even small heave movements will prevent large heave forces from developing. Large heave forces measured in soils during restrained heave tests are not necessarily indicative of a serious frost heave problem. Fortunately, from a practical viewpoint, the external and internal resistance required to reduce heaving of highway pavements to tolerable levels is fairly low, usually about 4 to 6 psi. This is only a small fraction of the pressure that would be required to prevent heaving completely.

Figure 10 shows the heave rates of several typical soils under various intensities of surcharge loads as measured in laboratory tests. The relationship between external load and heave rate follows the form of the work-energy curves plotted in Figure 9. Note that the effect of load on heave rate varies in different soils; increasing the load pressure on the glacial till and the silt retards heaving to a greater degree than the same load on the clay. Two explanations are possible in this case: (a) the clay contains considerably more fine particles and therefore more active thin film foci, and (b) the clay is more impervious than the other two soils and a greater subpressure probably developed in the soil voids thus adding to the external load. Because negative pressures were not measured in these experiments the magnitudes are not known. However, an indication of subpressures for one soil type is given in the data presented in Figure 6.

Theoretical formulations of frost heaving have been studied (7, 19, 21). Jackson et al (8) show that their theoretical formulation predicts heaving rate reasonably well for certain assumptions. Accurate knowledge of temperature gradients, heat flow rates, water transport (saturated and nonsaturated cases),

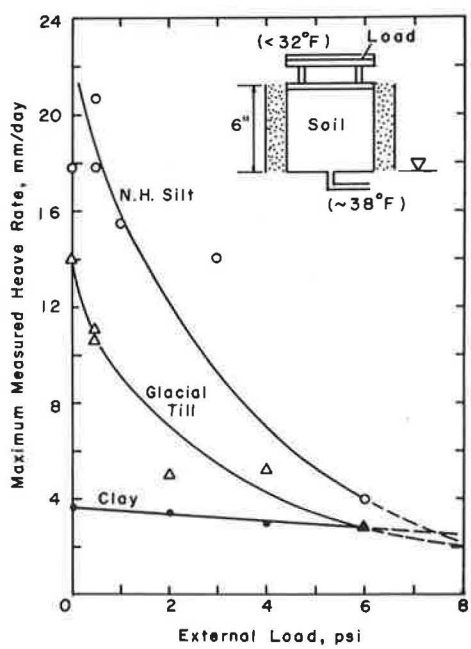

Figure 10. Experimental heave rates vs external (surcharge) load for several typical soils.

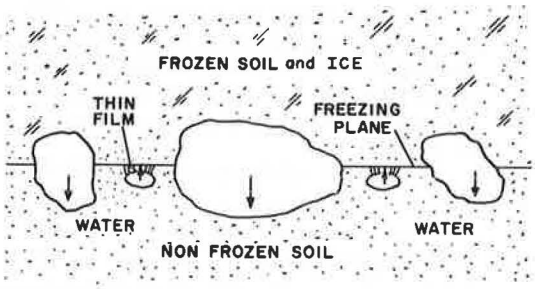

Figure 11. Restraints to heaving process by larger aggregates lying cross freezing plane.

subpressure gradients in the void water, and the relationship of all of these factors to the soil particles themselves and their packing is needed. Takagi (20) has formulated and solved differential equations for simultaneous heat and unsaturated water flow to the freezing front. Further intensive research should be directed to the physics and thermodynamics of the active film layer when undergoing phase transformation. The recent interest in "polywater" or "anomalous" water known to form in very fine glass capillaries may result in a better understanding of properties of soil water films.

SOIL STRUCTURE AND FROST SUSCEPTIBILITY

The presence of very small particle fines in a soil system influences frost behavior. It is apparent that the coarser soils contain considerably fewer fines per unit volume (also per unit cross section in a given plane) of soil and, therefore, cannot exhibit the same heave characteristics as silts. In gravelly soils, the larger particles or aggregate will lie across the freezing plane with a portion of the particle above and a portion below. Just as a load on the soil will act to resist the heaving forces, embedded coarse particles will offer frictional and displacement resistance to the heave forces located in the plane of freezing (Fig. 11). Figure 12 illustrates how the substitution of a large aggregate of comparable diameter for an equivalent volume of very small particles alters the physical soil system not only with respect to capillary water supply and the quantity of soil fines, but also heat conduction.

It has been claimed that heaving does not require the presence of fines and that with proper conditions heaving can be demonstrated in clean sands. Theoretically, this appears possible if the assumption of the active thin film is valid. In practice, however, the delicately precise conditions of temperature and heat flow balance required to maintain ice lens growth would be too difficult to achieve for the relatively small number of thin film loci in sand in the critical position of the thermal plane where the action is taking place. Furthermore, the lifting force would necessarily also be small and could easily be neutralized by small overburden pressures and interlocking resistance.

Beskow (2) reported that no heaving was observed with soil particles larger than 0.1 mm in diameter. However, LaRochelle (13) reports heave rates of about 0.8 to 0.9 mm per day in clean sand with zero percent passing the No. 200 sieve.

An important requirement for the occurrence of ice segregation is that water molecule replacement time and travel distance for new water molecules be very small, so that replacement can take place readily and permit the ice lens to grow while the freezing plane remains stationary. It can be visualized why an active layer over a large stone or aggregate could not be easily supplied with new water molecules; the distance of travel would be very much greater. The heat flow balance required to maintain the position of freezing front would be extremely critical when only a very few foci are involved, as in coarse-grained soils. A large number of activity loci permit a greater variation in heat flow without seriously affecting position of freezing front, providing water supply is readily available.

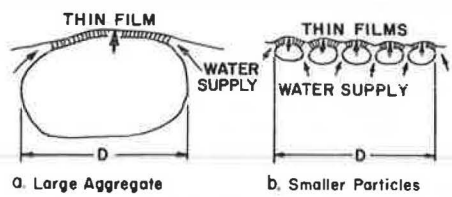

Figure 12. Heave force and water supply for large particle vs many small particles in the same projected area.

With an understanding of these considerations, we can apply this understanding in modifying a soil system to reduce its frost-susceptible behavior by reducing the number of fines, adding more coarse sizes to the system, or doing both. Addition of the coarse sizes performs two functions: it reduces the number of fines per unit volume of material, thus per unit cross section; and it provides more embedded resistance to heave forces. This sugests a number of other methods that might be used to counteract the heave forces: cementation of particles to resist separation and remove activity loci, use of fibrous tensile reinforcement in soil, direct loading, denial of water, and depression of freezing point of water.

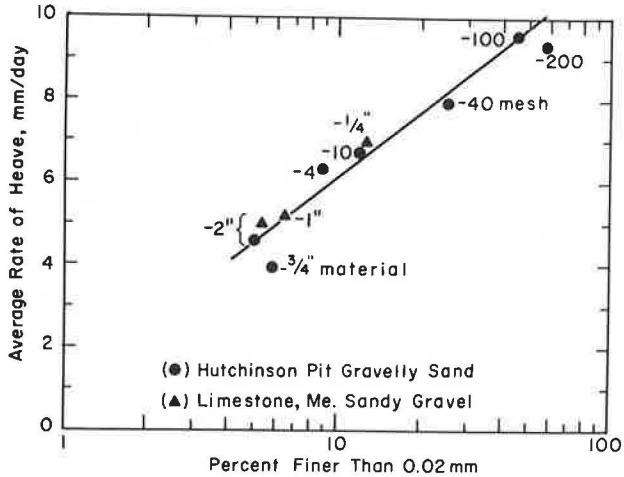

Figure 13. Heave rate vs percent finer than 0.02-mm size of "scalped" gradations.

Some interesting data on the effect of removal of fines or addition of coarse sizes on the heave rate of a base course type soil are given in the next section.

MODIFICATION OF FROST SUSCEPTIBILITY BY ALTERATION OF GRADATION

It was suggested earlier that frost susceptibility may be altered by removal of fines or by adding coarse aggregate. Data from two different experiments are available to illustrate the effect on frost-heave behavior of several frost-heaving base course type soils.

The results of one experiment gave the heave rates of two "dirty" gravelly sands (Fig. 13), both initially containing about 5 percent finer than the 0.02-mm size stone, with maximum size stone of 2 in. Specimens were frozen in the laboratory in the open system, using the standard Corps of Engineers test procedure (10, 14). Several different specimens were prepared from the basic material except that coarse sizes were "scalped" off successively as indicated in the figure, so that only the portion finer than a given size remained. Nothing else was altered. The compacted unit dry weights differed, however, because of the different gradation distribution. As the coarser sizes were removed, the percentage of the 0.02-mm size increased, and the measured heave rates also increased to the minus No. 200 mesh material, wherein a slight decrease in heave rate was measured. These data have been confirmed by similar tests on other soils. It can be concluded that adding or removing coarse sizes will produce changes in frost susceptibility. It would have made little difference in the example presented if we had started with the minus No. 200 mesh and added coarse sizes up to the 2-in. maximum; the effect would be the same. The total number of fine particles and their distribution are altered, and of course the overall permeability is changed.

Another set of experiments was tried at USACRREL during a cooperative effort with the University of New Hamphsire and the New Hampshire Department of Public Works and Highways (3). Two "dirty" base course soils were selected for experimentation to observe the effect on heave rate by reduction of fines by two methods: (a) by removal of fines (washing out some minus No. 200 mesh material); and (b) by adding some additional coarse sizes, ¼ to ¾ in., thus reducing the percentage of fines. The results, presented in Table 1, show that both approaches for reducing the proportion of fines decreased the frost susceptibility as measured by the heave rate. The implication of these test results is that it should be possible to alter a soil by judiciously blending

TABLE 1

SUMMARY OF GRAIN SIZE DISTRIBUTION MODIFICATION AND FROST-SUSCEPTIBILITY TESTS[a]

Type of Modification	Spec. No.	Soil			
		Bergeron Pit Gravelly Sand		Canterbury Pit Gravelly Sand	
		Percent Finer Than 0.02 mm	Rate of Heave (mm/day)	Percent Finer Than 0.02 mm	Rate of Heave (mm/day)
Original gradation	1	3.0	1.8	2.8	3.2
	2	3.0	1.5	2.8	2.6
Coarse added (¼ in. to ¾ in.)	1	2.5	1.0	2.0	1.8
	2	2.5	1.2	2.0	1.9
Fines removed (-No. 200 mesh)	1	2.1	1.2	2.0	1.6
	2	2.0	1.0	2.0	1.9

[a]After Biddescombe (3).

and mixing soils together or by washing out fines to obtain the required soil gradation characteristics. There is no need to depend on nature to provide the required gradation and reject a material because it lacks the correct index number.

It is believed that these results warrant further study to determine the most desirable gradation characteristics for the intended use and to develop ways and means of blending and mixing natural deposits or other artificially or mechanically prepared materials to meet man's needs.

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