Screenings from the Soil Research Lab

IOWA ENGINEERING EXPERIMENT STATION
IOWA STATE UNIVERSITY of Science and Technology
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FROST ACTION IN SOILS

The first known instance of frost action was a bad day for the family of man, brought about when Adam overlooked a wedding anniversary and came home in the early a.m. smelling of cigar smoke and hard cider. Directly thereafter was held the first World Championship Fight in the Garden. Adam lost, we don't need to be reminded.

Another type of frost action is called the frost heave, which occurs as an aftermath of too many ice cubes in the highball glass, waging war on the antifreeze. Prior to the heave, rather ordinary conversationalists are transformed into great wits who seem dull only to others; then they heave unto themselves, and they feel better.

In most frost action the troublemaker is ice, whether in the eyes of our true love, or in the icicles which form from her nose as she shovels out after a snow so we can drive to work. Ice is bothersome on roads or windshields, where it reduces highway speeds to the point where they are no longer lethal, and cuts visibility to a couple feet or so inside the car.

If we overlook occasional connubial glaciations, the most perplexing ice to the road engineer is not on top of the road but hidden away underneath. During the cold weather, ice forming in soil can easily boost a pavement as much as several inches, and later thaw and relax to a mucky hole. Thus winter brings trouble, and spring brings it to the surface.

Frost heave raises some dynamic problems on roads, contributing to spring break-up (illustrated).

Frost heave raises some grave problems in Alaska, for example in this Eskimo burial ground. Grim hairy reaper is grad student J. B. O'Sullivan.

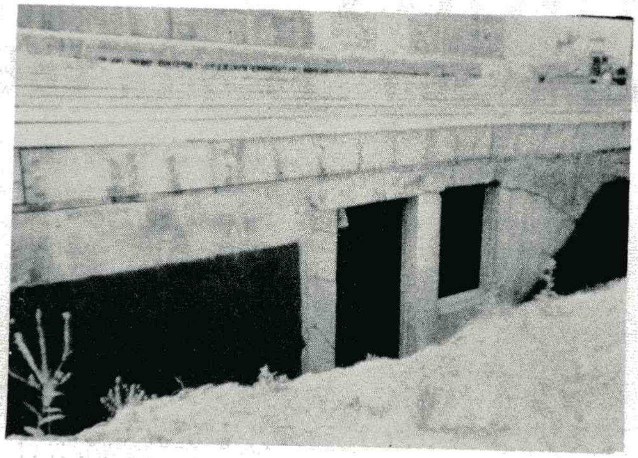
CONDITIONS

Three factors cooperate to cause frosty upheavals: the first requirement is some non-Freudian frigidity, in other words cold weather; the second is water, a customary raw material for ice; and the third is a frost-susceptible soil. If one of the conditions is not met, there is no frost action. For example, a ready way to avoid frost action is to have a warm winter. Write your Congressmen, or move to the Congo. Other ways to avoid frost action are reduce the availability of water, or change or exchange the soil.

Frost action is so common it probably occurs in your front yard, but it is seldom noticed unless some engineering structure does a shuffle. Smallest of buildings may rise and fall so uniformly the change is not noticed, except to stretch the outdoor plumbing. Under larger buildings the heave is seldom uniform, explaining why the floor in an unheated garage may mysteriously warp up at the edges and crack.

The most common prevention for such difficulties is to rest building foundations deeper than the frost can reach, ordinarily a matter of a few feet. In two general areas of construction this recipe is not feasible; these are the Arctic, where the frost goes too deep, and in building of roads, where the cost is too much. These are two admirable justifications for further small talk on frost action. Today we exclude permafrost; it will keep for later.

Return to Table of Contents



Abandoned apartment house foundation on silt soil, Fairbanks, Alaska. The foundation was deep enough had the building been heated, but no heat for one winter allowed the subsoil to freeze and flex muscles.

CLUES

Earliest conjecture on frost action began with country people wondering why some fields raised mostly boulders, without even the formality of a planting. Every spring a new crop emerged to engage the plow in combat.

Finally science found an answer: Water expands some nine percent on freezing, so water changing to ice underneath the boulders pushes them up. This sounded so logical that nobody questioned it for several hundred years, which shows the extent to which a fact can be distracting.

Twentieth Century

The coming of concrete pavement brought the effects of frost action into the open where they could be seen and stumbled over. Sometimes pavement slabs heaved, broke, and tilted to give a ride rivaling a roller coaster. This kind of infringement was looked down upon, especially by entrepreneurs of roller coasters. Something had to be done.

The magnitude of some of these frost heaves could not be accounted for by the old volume-change-on-freezing mechanism, but most engineers remained believers because the alternative was no religion at all. Nevertheless 3 inches of heave would require freezing of about a 30-inch layer of pure water or a much thicker layer of water plus soil, and people were wondering.

In 1765, frozen soil had been found to contain much more water than nearby unfrozen soil, but nobody paused to reflect on it. In 1914 a Swede named Johansson discovered that water moves to the freezing zone. Two years later a young University of South Carolina geology professor named Stephen Taber began assembling such facts in a new theory of frost heave.

THEORY, Part I

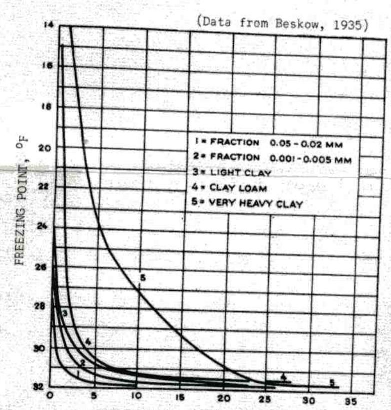
Taber knew that chemical crystals growing from a saturated solution exert enough pressure to lift weights, and he reasoned that the growing ice crystals should be able to lift weights likewise. He tried it. He placed metal weights on wet sands and clays and subjected the soils to freezing. True to prediction, weights resting on clay were raised. Those resting on sand were not; obviously more work was needed.

For the next 10 years Taber worked much and published little, virtues essentially the reverse of the practice today. In 1929 and 1930 he cracked open the vault and published three summary articles to try and explain frost action. He disproved that the 9 percent volume change of water on freezing is a major factor by substituting nitrobenzene, which shrinks on freezing and still causes frost heave. As he had first suggested in 1916, the major cause of frost heave therefore appeared to be gradual movement of water to the zone of ice formation.

Part II

Before launching on, we flash back to the lab where a young Michigan State research associate in soil physics named George Bouyoucos was busy investigating freezing points of water in soils.

Bouyoucos found that not all soil water freezes at 32 F; in fact in clays the freezing point may be many degrees lower. Furthermore the drier the soil, the colder it must be before water freezes.



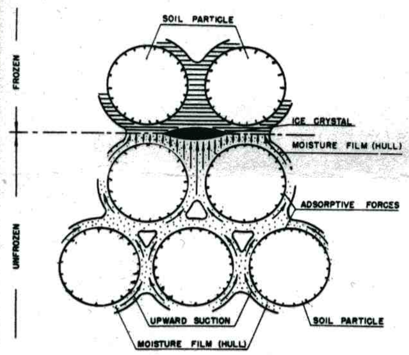
Apparently water loosely held in large soil pores freezes more readily than water in small pores, absorbed and held under pressure on the surfaces of mineral grains. An analogous condition occurs under glaciers or underneath ice skates; pressure lowers the freezing point and melts ice. Resulting instant water probably helps both to slide.

Return to Table of Contents

reenings
from the Soil Research Lab

Vol. 5, No. 1
1961

In the case of frost action, water held under pressure on grain surfaces remains liquid and readily seeps along to join the ice lenses. Freezing point depression is greatest in clays, which have tremendous grain surface, and least in sands and coarser materials. Perhaps this is a reason why sand doesn't frost heave (see Part I); where soil grains are large and freezing is rapid, grains are caught by the ice and entombed. But where soil grains are small, their comparatively thick coating of liquid water exerts hydraulic pressure and keeps them pushed away from the growing ice mass.



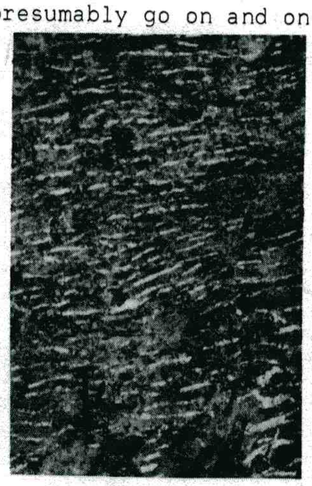
Upward flow of soil water toward growing ice crystal. (After Jumikis)

Part III

And where does the ice form? It depends how long it takes mein Frau to shovel the walks. Sometimes her very heart seems affected.

In soils, ice forms at the place where the water freezes, which seems logical. Because freezing occurs along an advancing front, ice tends to form in a horizontal layer (vertical behind a retaining wall). Furthermore water migrating to ice zone and freezing gives off heat which impedes advance of the freezing front.

This action could presumably go on and on and build a subsurface ice layer thicker than a glacier's toenail, but it doesn't. As water in a zone is used up, remaining water is more tightly held and less mobile, and rate of growth of the ice lenses is slower. Meanwhile cold temperatures are penetrating deeper, until they intercept relatively free water and start another ice lenses. The action then repeats.



Part IV

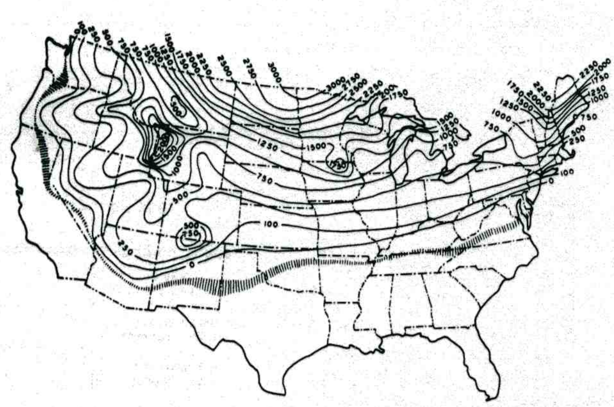
Finally, how does the water move and why does the ice push? An early suspicion was that water moves by capillarity caused by surface tension, but this would require air-water surfaces in the soil, and water appears to move to the freezing zone even though soil contains no air. Therefore molecular cohesion or "suction force" in the water has become the favored explanation.

As for where the ice gets its push, it relates to supercooling. No freezing point depression and there is no excess energy; it all goes to make ice. But a single cc of water freezing at -1 C (31.2 F) can theoretically lift a 12.5 kg (5.68 lb) weight one cm. Alternately it would lift 125 kg a distance of 0.1 cm, or 125,000 kg (28.4 T) a distance of 1 micron. Obviously surcharge should inhibit frost heave, and a pavement will heave higher than a bridge pier under the same conditions.

CONDITION COOL

The not-so-hot climate which gives frost action dips farther south than most Chambers of Commerce care to admit, but that's not our crop of oranges. Evaluation of sales records of long underwear substantiate that winters are milder now than in the good old days out on the farm. This is also reflected in other scientific indexes such as decline in sale of hot water bottles and increased popularity of shortie nighties, although there may be other factors.

One of the more reliable functions of clairvoyants in the Weather Bureau is to take temperature. Because rate of ground freezing depends on the amount the temperature goes and stays below 32 F, average daily temperature subtracted from 32 gives a pertinent measure called "degree-days below freezing." Or if the average comes above 32 the difference is "degree-days above freezing." Mathematics is almost routine when you know how.



Freezing index, degree days below 32 F. Shading indicates approximate limit of 1-foot-depth freezing one year in 10. For rough idea of depth of freezing in your area, read the map and check the graph. (After Corps of Engineers).

Return to Table of Contents

From field correlations by the Corps of Engineers a rough idea of depth of freezing under pavement can be obtained from the preceding graph by

$$X \text{ (in.)} = 1.4 \sqrt{F}$$

Examples: F = 3000, X = 77"; F = 1500, X = 54"; F = 750, X = 38"; F = 100, X = 14".

The above formula is but rough, and may be off by a factor of one-half because depth of freezing depends on other things besides the freezing index. The modified Berggren formula for depth of freezing is

$$X = \lambda \frac{48 \ kF}{L} ,$$

which brings in thermal conductivity k, latent heat L, and a correction λ, in addition to surface freezing index F.

The formula points out some perplexities: Compact soils freeze deeper than loose soils because of change in k. Dry soils freeze deeper than wet soils because water contributes the latent heat L; the highway engineer therefore builds a long ice box.

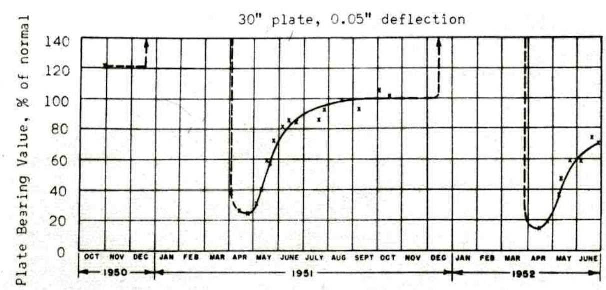
Finally the correction factor λ depends on how warm the soil is to start with--in other words how much volumetric heat is contained due to a mean annual temperature above freezing. For saturated soils and in northern climates λ is close to 1.0, whereas in dry soils or farther south λ may be as low as 0.5.

Freezing index in the formula ideally represents temperatures at the ground surface, which probably differ from air temperature data supplied by the Weather Bureau. The exact relationship is a very tricky problem in heat transfer, and involves such things as color and texture of the surface, angle of the sun, and which way the wind blows on Thursday. All this has not been worked out yet. For pavements F is sometimes multiplied by 0.6.

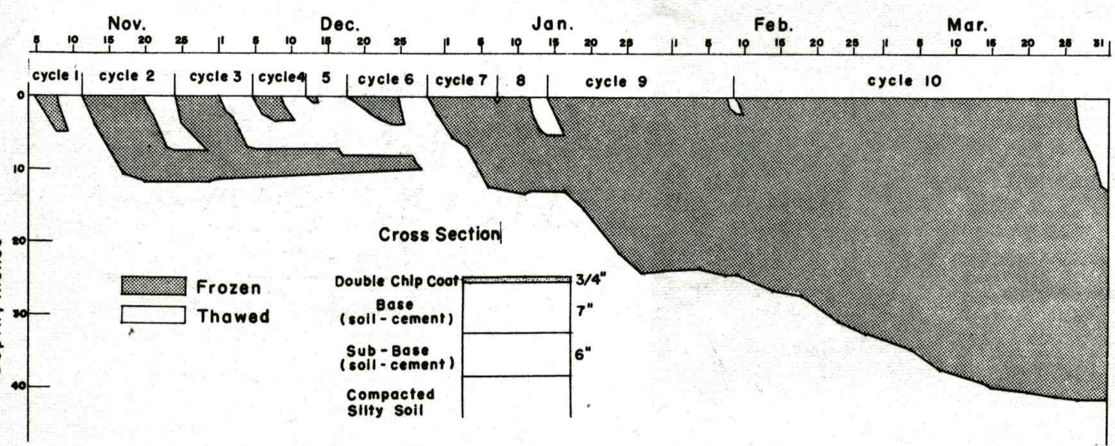
Ice Breaking

Comes the hot heart of spring, frozen ground thaws, and the ice contained therein melts. Thawing is mostly from the top, and rate may be predicted from the Berggren equation, except that k is lower because it represents heat penetration through thawed soil rather than through frozen soil, and F is a thawing index (degree-days above freezing).

All soils exposed to cold weather freeze, but many don't misbehave and invite in ice lenses. It's a matter of character and upbringing. Soils with ice lenses thaw and mingle to form mud, especially because thawing from the top keeps the water perched in its icy bucket. Only when thawing is complete can normal downward drainage resume. Meanwhile the road is soft as baby's smile or something else. Graph below shows strength of a gravel base course on a frost-susceptible soil, Maine.



No winter is complete without an occasional thaw to make us wish for spring. Freeze-thaw cycles are devastating to strength of saturated



Calculated depths of freezing and thawing of a road in central Iowa, winter 1959-60.

Return to Table of Contents

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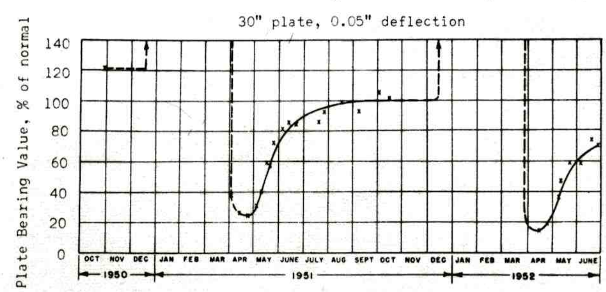

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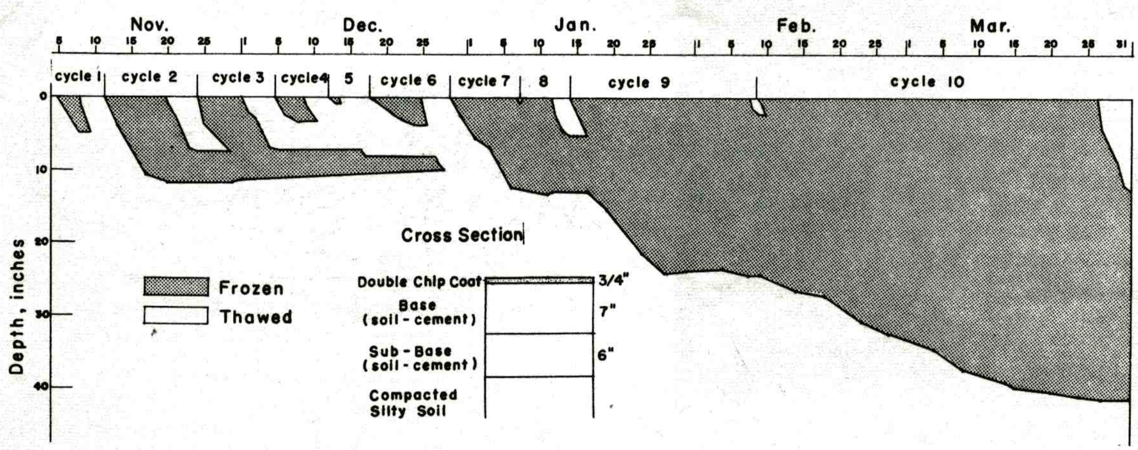

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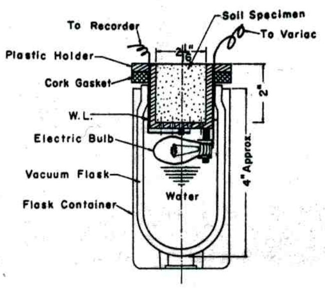
Return to Table of Contents

eenings
from the Soil Research Lab

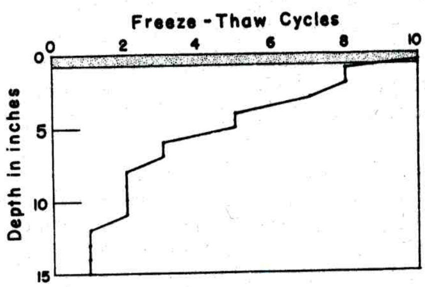
Vol. 5, No. 1
1961

soil whether the soil heaves or not, because of that old 9 percent volume change of water on freezing. Ice lensing helps the soil to be saturated, but is not required, although alternate freeze-thaw also increases frost heave by permitting periodic additions of more water.



Modified British freeze-thaw test apparatus used at I.S.U. Soil specimen suffers all the joyous discomforts of a duck hunter--wet seat, feet in water, and freezing from the top down. Electric seat heater and vacuum insulated boots keep the water from freezing.

The graph below shows a year's total freeze-thaw cycles in the pavement of the preceding page. Obviously the top part of a pavement takes more abuse than the bottom.



Freezing control

One way to stop frost heave is to stop freezing. To this goal Swedish roads have been built on blocks of moss, straw, or moor (peat), and the Corps of Engineers suggests slag or cinders. Frost penetration into moss is about half as fast as in wet sand; frost penetration in slag or cinders is about two-thirds as fast.

CONDITION WET

Forgive us for detailing the obvious, but the second requirement for frost action is water for ice. Cool some dry soil below freezing and it doesn't harden, heave, or even hiccup; it just gets cold.

Soil water fits in one of three political camps: Free water is found below the water table and is what the well drillers are after. Capillary water occurs above the water table, held up by capillarity, or forces of surface tension. Hygroscopic water occurs even in air-dry soil, where it is chemically adsorbed in thin films around soil grains, and has the lowered freezing point needed for migration to the ice lenses.

If hygroscopic water borrowed for ice lenses is replenished from the outside, the system is "open," and heave goes on and on, or rather up and up. If water is not replenished the system is "closed."

Open systems are the rule, as proved by success of water witches, the secret being that water is underneath about anywhere you care to drill a well. Some heavy clays are so impermeable that the system is practically closed; ice lenses form, but at expense of water in adjacent soil. Therefore a clay soil may shrink rather than heave! Graduate students will please leave the room, go home and think this over and write a term paper on it, due tomorrow. The rest of you may cogitate for the remainder of this paragraph.

Apparently ice lenses forming in a closed system remove sufficient moisture from clay soil immediately below that it desiccates and shrinks. Comes spring the soil moistens and springs back up. Freezing shrinkage accounts for apparent winter heave of many bridges and culverts; actually soil and pavement on either side temporarily have gone down.

Swingin' in the Rain

A fourth class of water and the only kind conveniently attributed to leaky angels is rain, which in showers brings May flowers. Coming down to earth, rain hastens thawing of frozen soils and readily makes mud, ice lenses or no. Therefore a road needs a tight roof such as pavement. Pavement halts rain action but not frost action.

Moisture Control

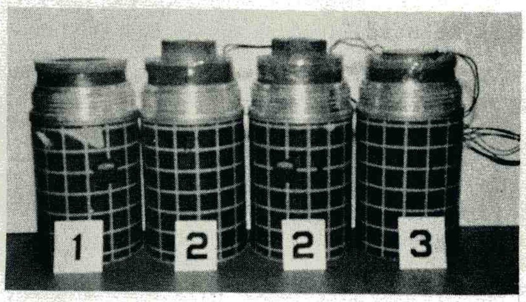
Even before the word was out that frost heave is dictated by availability of water, patents had appeared, which shows how far some inventors run ahead. A patent in 1888 prescribed lateral drains and a waterproof membrane, and in 1929 Taber suggested use of a membrane of coarse sand to cut off movement of adsorbed water toward the ice zone.

A less absolute approach which is more often heeded is to either raise the ground or lower the water table. Highway engineers generally prefer to raise the ground, building roads on a fill. As part of his extensive studies of frost action the Swedish authority Beskow found that doubling the distance to the water table would cut frost heave about one-half.

A method not directed at controlling frost heave, but effective for reducing spring sloppiness or "frost boils," is to build the road on

Return to Table of Contents

sand- or gravel-filled trenches which act as drains. The proper name is "French drains," probably because of all that salt air in Paris.



Freeze-thaw test specimens showing heave. (1) Before freezing; (2) after freezing; (3) same with sand sub-layer to reduce availability of moisture. Soil is a silt (loess) containing 2 % portland cement; about 6 % cement prevents heave.

CONDITION SUSCEPTIBLE

Because the first two conditions for frost action, climate and moisture, are rather difficult to control, highway engineers are forced to take elegant precautions with the third, which is soil.

Whereas some soils frost heave inches or feet, other soils under the same conditions show complete disdain and don't heave at all. Coarse sands and gravels are generally safe and stable; hence their popularity in roads. Their hygroscopic water is insufficient for even a token uprising.

Silts are the real agitators and fomenters of revolution. Silts have larger surface area which holds mobile hygroscopic water, and they have high permeability, which means an open system with plenty of water available for ice lenses. In clays frost action is slowed because of low permeability, although the potential for unrest is still there.

Soil Control

Obviously one way to avoid frost action is avoid use of silty or clayey soils in the freezing zone. A much-used empirical criterion established by A. Casagrande is that any soil containing more than 3 percent finer than 0.02 mm (20 microns) is suspect. Where such soils occur, the engineer can cover them so they don't freeze, usually a matter of 3 feet or more. Then no more worry, except who is going to pay for it.

The above method works well for airfields where pavements must be thick anyway, but costs too much for highways. The alternate plan is let traffic tolerate heave and hope that it is uniform, and make the pavement sturdy enough to still carry the loads when the soil is weakest.

Admixtures

Several soil stabilizing agents prevent frost heave, either by cementation, as in soil-cement, or by decreasing water freezing temperature, as with salt, or by reducing soil wettability and permeability, as with asphalt.

In general the amount of portland cement or asphalt required to produce frost resistance is in the realm of the amounts needed to make a stabilized base course, and few states care to install a base course 3 to 5 feet thick. Heave in silts may be prevented by about 2 percent calcium chloride, but the latter is ordinarily applied only in the upper 6 to 12 inches of road.

A very nifty scheme used by the Iowa State Highway Commission is to drill 6-foot-deep holes at 5-foot intervals and back-fill with gravel and calcium chloride. The holes do not prevent frost heave, but act as vertical drains for excess perched moisture during the spring thaw.

Similar and different from chlorides is non-alcoholic waste sulphite liquor from northern paper mills. The brew depresses the freezing point only a few degrees, not 10 or 20 as in the case of chlorides; nevertheless the rate of ice crystallization of supercooled solutions is greatly retarded, and frost heave is reduced. Probably molecules plug growth sites on the ice crystals. Like chlorides, sulphite liquor slowly leaches down.

Other chemical additives such as quaternary ammonium chlorides (sour hog fat) are effective in trace amounts but most likely would need to be incorporated into the road as it is built.

REFERENCES AND ACKNOWLEDGMENTS

Since about 1948 the Highway Research Board has been the major clearing house, sounding board, and tuning fork for soil frost action research. Recent reading: HRB Special Reports 1 (A. W. Johnson literature review 1765-1951), 2 (symposium), and 40 (soil water); and annual bulletins 71, 96, 100, 111, 135, 168, 207, and 218. See also Jumikis, "The Frost Penetration Problem in Highway Engineering," Rutgers Univ. Press, 1955.

Soil freezing studies at I.S.U. are sponsored under Project HR-1 of the Iowa Highway Research Board with funds from the Iowa State Highway Commission.

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Return to Table of Contents