FROST ACTION IN STABILIZED SOIL MIXTURES

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SYNOPSIS

The first progress report on the investigation of frost action in stabilized soil mixtures being carried on as part of the research program of the Joint Highway Research Project at Purdue University presents the results of studies which are substantially complete at the present time These include the relation to frost action in stabilized soil mixtures of (1) gradation of soil mixture, (2) type and percentage of admixture, and (3) moisture content at the beginning of the freezing period

The testing equipment and technique, with minor modifications, were similar to those of Taber, Casagrande, and Beskow

The materials tested include natural sandy clay and graded soil mixtures combined with sodium chloride, calcium chloride, calcium oxide, portland cement, tar, emulsified asphalt, cutback asphalt, and road oil

One hundred and sixty specimens compacted in the laboratory in molds 3 in in diameter by 7 in high were tested Under similar conditions of temperature variation, all specimens were frozen slowly from the top down with a supply of free water available to their lower surfaces

The results include curves of rate of heave, curves of effect of various admixtures, and charts which show percentages of heave and changes in moisture content for various conditions of admixture and initial water content

The results indicate that damaging frost action can occur under certain conditions in most stabilized soil mixtures The curves and charts, which can be discussed only with their aid, indicate significantly trends in the effects of admixture Investigations now in progress cover the possibilities of dangerous frost action conditions occurring in stabilized mixtures in the field

In May, 1938 an extensive program of frost action research was begun by the Purdue Joint Highway Research Project with its first objective the investigation of the relative effects of frost action in various types of stabilized soil road surfaces and bases now in common use

The experimental program in progress includes studies of the influence of the following items on destructive frost action in stabilized soil mixtures

1 Various soil mixtures
2 Various types of admixtures
3 Various percentages of admixtures
4 Moisture content at beginning of freezing period
5 Density at beginning of freezing period
6 Loss in moisture content under various conditions of field curing and exposure
7 Increase in moisture content prior to freezing period by capillary flow or surface infiltration
8 Accurate correlation between temperatures of soil in field and laboratory temperature gradients
9 Correlation between results of field exposure and laboratory tests

The investigation of the first four is substantially complete, and the results will be presented in this report The investigations of the last five items are not sufficiently complete to be reported at this time

Review of Physical Processes of Frost Action

The expansion in volume of pure water on freezing at atmospheric pressure is approximately 9 per cent If the total volume of a saturated soil consists of two thirds solid matter and one third water filling the voids, the expansion of the soil mass due to the freezing of the water in its voids cannot amount to more than 3 per cent of the original volume of the frozen portion of the soil mass. Since authenticated measurements of expansions as great as 60 per cent of the original volume of frozen soil masses have been published, it is obvious that factors other than the expansion of the water originally contained in the voids of frozen soil must enter into the physical process of frost action These additional factors and the entire physical process of frost action have been systematically studied by Taber (1 to 6 inclusive),[1] A Casagrande (7), Beskow (8), and others

Taber has summarized his hypothesis (p 173 in reference 6) as follows

"Frost heaving is due to the growth of ice crystals and not to change in volume (of water on freezing) Pressure is developed in the direction of crystal growth which is usually determined chiefly by the direction of cooling Excessive heaving results when water is pulled up through the soil to build up layer or lenticular masses of segregated ice, which grow in thickness because water molecules are pulled into the thin film that separates the growing columnar ice crystals from the underlying soil particles"

Taber states that in most of his experiments, segregation of ice into layers or lenses was accomplished by a single freezing cycle at a "uniform freezing rate" In other words, after placing his specimens in a freezing cabinet, Taber lowered the temperature of the air above the tops of the specimens to constant value, at which it was kept during the duration of the freeze Early in Taber's investigations soils were subjected to repeated cycles of freezing and thawing, and it was found that prompt refreezing after thawing resulted in greater ice segregation and heaving than occurred on the first freezing Taber states "The first freeze breaks up a consolidated soil, increasing permeability and reducing its tensile strength so that less resistance to heaving is offered when refreezing occurs Refreezing is not necessary to explain the formation of ice layers and excessive heaving, for a surface uplift amounting to over 60 per cent of the depth of freezing has been obtained as a result of only one freeze. Repeated cycles of freezing and thawing introduce no new factors and do not alter the mechanics of frost heaving"

In Taber's experiments natural conditions of soil freezing were duplicated by exposing the tops of the specimens to freezing temperatures, insulating the sides with dry sand, and maintaining the bottoms, whether sealed (closed system), or open in a pan of water (open system), at a temperature above the freezing point corresponding roughly to normal soil temperatures below the zone of frost penetration With minor variations, Taber's technique was followed by Casagrande and Beskow A large amount of evidence, collected both in the field and in the laboratory, has shown that Taber's fundamental hypothesis and experimental technique are correct Casagrande has shown further (p 170, reference 7) that during a normal winter (1928–29 in Cambridge, Mass), with the exception of a few inches immediately below a highway slab, soil once frozen remains frozen during the entire period of winter weather Casagrande's observations show strikingly that a cumulative diagram of degree-hours or degree-days of freezing is almost exactly duplicated by a plot of frost heaving against time and that a plot of frost penetration is almost exactly a mirror image of the plot of frost heaving (Fig 1)

Beskow points out (p 226, reference 8) that the direction of the growth of ice layers, and the direction of expansion or

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[1] Number in parentheses refer to list of references at end

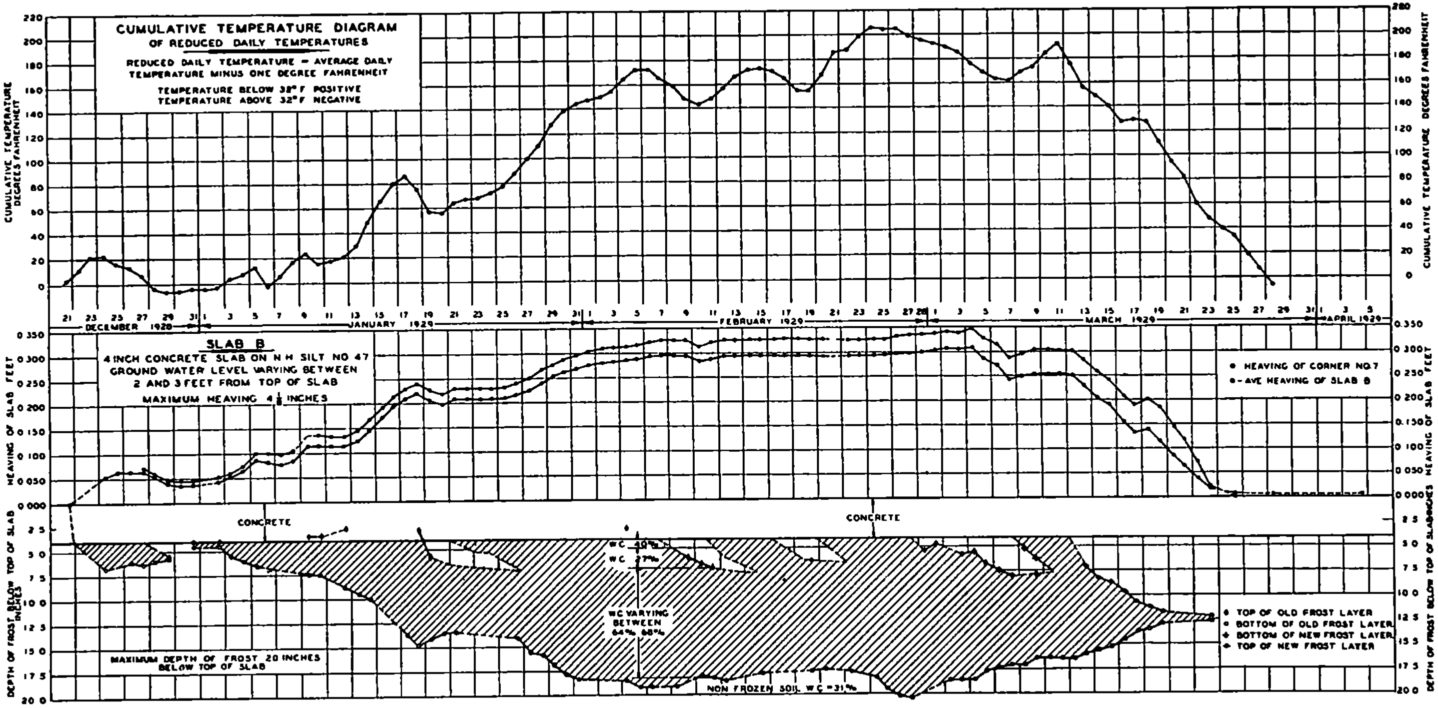


Figure 1. Curves Showing Relation of Cumulative Temperature, Frost Heaving, and Frost Penetration

heave, are governed by three factors: (1) pressure, (2) direction and rate of heat transfer, and (3) soil stratification and fissures He states that ice crystals tend to grow in the direction of minimum resistance to expansion and in the direction of heat transfer. Under natural conditions in the ground the minimum resistance to expansion is vertical, and the direction of heat transfer is vertical from the warmer soil below to the freezing temperatures above the surface Thus the crystals most frequently grow in a vertical direction and the ice lenses extend horizontally in the fissures opened by vertical growth Planes of stratification, which are frequently horizontal in soil, offer planes of minimum resistance to separation or expansion of ice crystals Thus, ice lenses tend to follow planes of stratification with the ice crystal growth normal to the planes In top-soils, in which fissures run in all directions, and in clays, in which shrinkage through loss of water to ice lenses offers opportunities for expansion in many directions, the horizontal stratification of ice lenses is not so well defined as in silts and silty sands

Taber states (p 127, reference 5) "In indurated clay, or in clay that has been thoroughly consolidated artificially, the layers of segregated ice are clear (for the most part), solid, and very sharply separated from the clay The ice usually shows a satiny luster because of the parallel orientation of the ice prisms and the presence of small filiform cavities filled with air, oriented in the direction of crystal growth Both thickness and spacing of the ice layers tend to increase with distance from the cooling surface (decrease in rate of heat transfer) The total thickness of the ice layers, as closely as can be measured, equals the amount of surface uplift, and the water content of frozen clay between the ice layers is the same as that of clay below the depth of freezing These observations prove that heaving is due to the formation of ice layers, the freezing of interstitial water being of little or no importance."

In order for layers of segregated ice to grow in a soil while the water content of the soil itself undergoes little change, a continuous supply of water must be available. Beskow shows that a necessary condition is that the soil be in a state of capillary saturation at the beginning of the freezing process With the soil in this state, two conditions will permit sufficient supply of water from below (from the source of capillary saturation) to form segregated ice lenses first, very slow rate of heat transfer such that the frost line remains practically at a constant elevation leaving all soil below in an unfrozen state; or second, decrease in freezing temperature of water in very small voids of the soil so that, while the water in the large voids near the frost line is frozen and ice crystals are growing, a supply of unfrozen water can reach the growing crystals through the smaller voids The second condition is the most common for frost action in nature Studies by Bouyoucos (9, 10), Jung (11) and Beskow (pp 33–41, 223–224, reference 8) show that the freezing temperature of water decreases with the diameter of the soil grains, or the diameter of the voids within which it is contained The cause, as stated by both Jung and Beskow, is the effect of the forces of adsorption from the particles of soil The water farthest from the particles of soil is least influenced by their adsorption force and therefore has the highest freezing point The nearer the water is to the soil particle the greater the adsorption and therefore the lower the freezing temperature This is in accord with Terzaghi's explanations of the behavior of water at varying distances from the soil grain to which it is held by adsorption Above certain grain diameters, or certain void diameters.

the effect of layers of adsorbed water on the freezing temperature of the major portion of the water in the voids becomes negligible Thus in gravels and coarse sands the freezing temperature is unchanged for practically all the water in the voids and ice segregation can occur only under the condition of very slow rate of heat transfer In order for ice segregation to occur under normal conditions of heat transfer, a certain minimum percentage of smaller grains and, consequently, smaller voids, must be present to supply water for the growth of ice crystals

Casagrande states (p 169, reference 7) "Under natural freezing conditions and with sufficient water supply one should expect considerable ice segregation in non-uniform soils containing more than three per cent of grains smaller than 0 02 mm and in very uniform soils containing more than 10 per cent smaller than 0 02 mm No ice segregation was observed [in studies at the Massachusetts Institute of Technology and throughout the state of New Hampshire] in soils containing less than one per cent of grains smaller than 0 02 mm , even if the ground water level was as high as the frost line " Studies by Taber and Beskow show that the severity of frost heaving increases as the percentage of grains smaller than 0 02 mm increases, being very severe in silts but somewhat less in very plastic clays, probably due to decrease of the freezing point of a large percentage of the water in the voids and great resistance to the flow of water.

In reporting on Jung's work on the effect of the rate of freezing, Beskow states (p 225, reference 8) "As the rate of freezing is successively increased, the ice segregations become smaller and more diffuse until they wholly disappear, and the soil freezes homogeneously Even a heavy clay was brought to freeze homogeneously (as opposed to heterogeneous freezing of clay and ice lenses) at an exceedingly rapid rate of freezing The author's [Beskow's] freezing experiments have shown the same effect, though limited to rates of freezing corresponding to natural conditions "

The conclusions of these investigators can be summarized as follows

(1) Destructive frost heaving is almost invariably associated with the formation of segregated ice

(2) The total amount of frost heaving is very closely equal to the sum of the thicknesses of all layers of segregated ice in the frozen soil

(3) The total amount of frost heaving is in direct proportion to the increase in total water content of the frozen soil

(4) The soil must have a water content at least equal to a state of capillary saturation for ice segregation to take place

(5) A supply of water must be available for the growth of ice crystals, either from some portion of the soil itself or from some external source, e g ground water table

(6) For normal field conditions of temperature a certain minimum percentage of grains smaller than 0 02 mm is necessary for ice segregation

(7) One, slow, gradual decrease in temperature well into the freezing range is necessary and sufficient to cause ice segregation and frost heaving Subsequent thawing and refreezing may increase the severity of the frost heaving but will not change the basic action

(8) A cumulative curve of degree-hours of freezing plotted against time is a qualitative measure of the increase of frost heaving with time

(9) The following factors are all necessary for ice segregation and frost heaving If any one of these factors is not present, frost heaving will not occur

a) Capillary saturation of the soil at the beginning of or during the freezing process
b) A free supply of water from within or without the soil.

c) A minimum percentage (3 to 10 per cent) of grains smaller than 0 02 mm
d) A gradual decrease in temperature of the air above the soil below freezing temperatures

Basis for this Investigation

The investigation, for which this is a progress report, is based on and is a continuation of the frost action studies outlined above Much of the equipment and experimental technique has been adopted directly from those used by Taber, Beskow, and Casagrande Of the previous investigations with which the author is familiar, only the studies of Beskow have dealt with the effect of admixtures to the soil or water on the reduction of frost heaving Beskow finds (pp 100–105, 232, reference 8) that sodium chloride in very dilute concentrations increases the rate of heaving, while in concentrations greater than approximately ½ per cent it decreases the rate of heaving The other three admixtures which Beskow investigated, calcium chloride, sulphuric acid, and sulphite leach, all diminished the rate of frost heaving, usually to an extent which increased with the strength of the solution

In order to fill an apparent gap in the knowledge of the behavior of stabilized soil mixtures, this investigation has undertaken to show the effect of frost action in soils treated with various types and percentages of admixtures under various conditions of initial moisture content and initial density At some points in this progress report, it may appear that rather artificial means have been used to attain certain initial conditions of moisture content and density The plan of attack is to investigate first the effect of the various conditions outlined above and then to study the possibilities of such conditions occurring in the field

Correlation of the laboratory tests with the results of field exposure is, of course, dependent on the conditions of field exposure of recently constructed test sections Until conditions of water-content, water availability, and gradually decreasing temperature gradient so combine as to produce ideal conditions for ice segregation and frost heaving, correlation will be difficult Field experience has shown that it is not unusual for several years to elapse between times of favorable combination of all elements at a given section of highway

Materials Tested

SOILS

The Joint Highway Research Project at Purdue University has constructed two test roads in order to observe the effects of field exposure and traffic conditions on various types of stabilizing soil mixtures and admixtures In order to correlate laboratory observations with field exposure, most of the mixtures and admixtures included in the test roads are included in this study A sandy clay, which forms the sub-grade for the test roads and which was used in making up the test road sections, was used in the preparation of the laboratory specimens This particular sandy clay is a typical, dangerous, frost-heaving soil When tested in the frost action cabinet, a heave of 59 6 per cent of the depth of frost has occurred as compared with the findings of other investigators (Beskow (8) and Taber (5)) which show that a heave of 60 per cent is about the maximum to be expected under ideal conditions

The gravel used in the graded mixtures was pit run material The sand used in the sand-clay mixtures was a fairly uniform, washed, concrete sand The graded mixture resulting from the combination of 16½ per cent of the sandy clay with 83½ per cent of the pit run gravel is typical of the mixtures in common use in stabilization work and falls within the recommendations of most highway organizations.

The grain size curves for the individual soil types are shown in Figure 2 and for the various mixtures in Figure 3. Table 1 gives the Atterburg limits and other data on the soils used

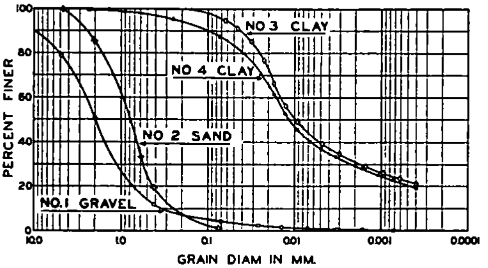


Figure 2. Grain Diameter Distribution Curves for Individual Soil Types

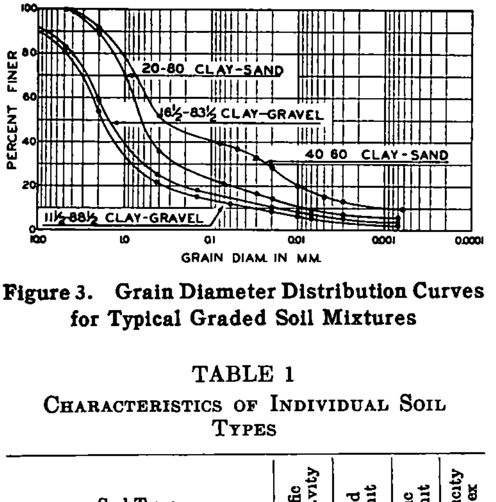


Figure 3. Grain Diameter Distribution Curves for Typical Graded Soil Mixtures

TABLE 1

CHARACTERISTICS OF INDIVIDUAL SOIL TYPES

Soil Type	Specific Gravity	Liquid Limit	Plastic Limit	Plasticity Index
No 3 Sandy Clay	2 69	46 1	18 6	27 5
No 4 Sandy Clay	2 72	45 6	18 3	27 3
No 1 Pit Run Gravel	2 72			
No 2 Concrete Sand	2 76			

ADMIXTURES

The stabilizing admixtures used in this investigation can be classified into two general groups on the basis of their physical action.

1. *Water-insoluble binders*, such as bitumen and portland cement which act as cementing agents, increasing the resistance to expansion

2. *Moisture-retentive chemicals*, such as calcium chloride, which reduce the thickness of adhesive water films on the soil particles through increased surface tension, increasing the cementing action of the clay binder, and, in general, reduce the freezing point of the water in the soil mixture

The bituminous materials were tars, emulsions, cutbacks and road oils Specifications for these materials are given in Table 2.

Other admixtures used and reported on in this paper are portland cement, calcium chloride, sodium chloride, and calcium oxide

Distilled water was used in all laboratory mixtures

EXPERIMENTAL PROCEDURE

PREPARATION OF TEST SPECIMENS

Throughout this investigation specimens have been prepared with physical characteristics (density, moisture content, percentage of admixtures, etc) as nearly as possible like those that might occur in a stabilized soil road surface or base

Mixing and Molding The clay to be stabilized was air dried and carefully pulverized with mortar and pestle in order to break down all lumps without crushing the soil particles. The moisture content of the clay, when air dried, was approximately three per cent The gravel and sand were also air dried to a moisture content of approximately one per cent

A batch consisted of enough material to mold two identical specimens, only one of which was completely tested, the other being carried along as a substitute in case of breakage during handling and curing of the test specimen. In designing a mixture, the weight of dry soil (clay, sand, and gravel) was taken as 10 lb., the admixture computed as a percentage of the dry soil weight, and the moisture content computed as a percentage of the combined dry weights of soil and admixture. All specimens were molded at approximately the optimum moisture content for the particular type of mixture as determined by the Proctor procedure. The sample calculations following illustrate the design of a mixture.

TABLE 2

Specifications of Bituminous Materials Used in Frost Action Investigation

Indiana Specification Designation	MC-1	RC-3	SC-3	TC	TM-2	AES-1	Bitumuls Stabilizer
Specific Gravity @ 25°C			1.040	1.166	1.181		
Specific Gravity @ 15.5°C	934	960					
Furol Viscosity @ 77°C	136″					12″	
Furol Viscosity @ 140°C		371″	223″				
Engler Viscosity @ 40°C				11.8	66.1		
Flash Point (Cleveland open cup) Deg. F			380				
Flash Point (Tag open cup) Deg. F	170	142					
Loss on Heating, 163°C, 5 hrs, %			1.58				
Distillation							
% off at 170°C				0.9	0.1		
225°C	7.0	9.5					
260°C	27.5	16.0				46.75	41.2
300°C				31.7	17.4		
316°C	37.0	21.5					
360°C	42.0	23.5					
Oil Portions, %						2.5	0.5
Water, %	Trace	None	Trace	Trace	Trace	44.25	40.7
Residue, %				67.3	81.2		
Penetration of Residue	201	92					65
Specific Gravity of Distillate				1.032	1.021		
Bitumen Soluble in CS_2, %				92.0	93.6		
Bitumen Soluble in CCl_4, %	99.7	99.5	99.8				
Inorganic Matter Insoluble, %				0.11	0.03		
Penetration of Residue			73.6				
Ductility @ 77°F	28.0	8.5					
Ductility @ 39.2°F	110+	110+	110+				
Melting Point of Residue (B + R) °C				40.4	34.0		
Float Test of Residue @ 50°C						24″	

Composition:

20% Sandy clay (containing 3% moisture)
80% Gravel (containing 1% moisture)
} Based on weight of dry soil.

8% Cement—percentage of dry weight of soil.
9% Water (optimum moisture content)—percentage of dry weight of soil and cement

Let dry weight of soil = 10 lb. = 4530 grams
Clay required 0.20 × 4530 × 1.03 = 933 g
Gravel required 0.80 × 4530 × 1.01 = 3660 g
Cement required 0.08 × 4530 = 362 g
Water required (.09) (4530 + 362) − (.03) (933) − (.01) (3660) = 376 c.c.

The procedure in combining the soil mixture with admixture and water depended upon the type of admixture. Portland cement and quicklime were mixed with the dry soil before the addition of the water, the bituminous materials were added after the water had been completely mixed with the soil; the salt and calcium chloride were dissolved in the water before adding to the dry soil.

The soil, water, and admixture were thoroughly mixed by hand to insure uniform distribution of all ingredients.

Using a 5½-lb. rammer with a 2-in. diameter tamping face and a cylindrical brass mold similar to the Proctor mold (12), the soil mixture was compacted into the mold in four equal layers by 14 blows of the rammer dropped 1 ft. on each layer. The special mold used in this investigation had an inside diameter of 3 in., was 7 in. high, and contained a volume of $\frac{1}{35}$ of a cu. ft. The laboratory apparatus used in mixing and molding specimens is shown in Figure 4.

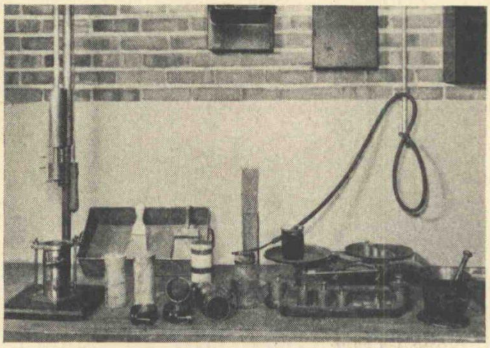


Figure 4. Apparatus Used in Preparing Mixtures and Molding Specimens

After compaction, the two specimens were pushed out of the molds by means of a compression machine, weighed and inspected, the better of the two chosen as the test specimen, and the other retained as a substitute.

The remaining portion of the batch, usually about 500 gm., was oven dried and the true moisture content of the mixture computed.

Curing. In order to secure the maximum benefits from certain types of admixtures, a period of curing under proper conditions is necessary. All soil-cement specimens were cured in a standard moist closet for 10 days or more; all bituminous mixture specimens were air cured in the laboratory at 70°F. for 10 days or more. Although the other types of mixtures do not require curing, some have been cured to a low moisture content.

The variable moisture contents resulting from the different conditions of curing led to the division of the specimens into the *dry test* and *wet test* groups. (See Figs. 13, 14, and 15.) In the dry test group are specimens of all types which, regardless of whether they require curing or not, were cured to a low moisture content and tested in that condition. In the wet test group are (1) specimens which did not require curing and were tested, as molded, at the optimum moisture content and (2) specimens which required curing, were cured to a low moisture content, and then the water was restored to approximately optimum before testing.

The purpose of including both dry and wet test specimens (referring to the condition of the specimen at the beginning of the freezing test), in spite of the established fact that capillary saturation is necessary for ice segregation, was to establish the rapidity with which water could rise in the specimen under freezing conditions and cause ice segregation. It is probable that stabilized surfaces and bases will be found in both conditions in the field at the beginning of the freezing period. While an initial condition of capillary or complete saturation is undoubtedly the most dangerous condition, the possibility remains that some stabilized mixtures will always have a water content less than capillary saturation at the beginning of the freezing period, even with a supply of capillary water from the ground water table available.

Saturating Equipment and Procedure. In order to accelerate the process of saturating the inherently water-resistant specimens, particularly the cured, bituminous types, the apparatus shown in Figure 5 was constructed. The drawing of one of the units, Figure 6, shows the details of the apparatus.

The sides of the specimen to be saturated were painted with paraffin, and the specimen was then slid into the pipe which had been heated to a temperature slightly above the melting point of paraffin. Upon cooling the space between the pipe and specimen, which differed in diameter by 0.067 in., was uniformly filled with paraffin, and the escape of water by that route was prevented. It was found by experimentation that a pressure head of approximately 30 lb. per sq. in. applied for 24 hr. was sufficient to restore to approximately optimum moisture content, or to saturation, any of the types of specimens considered in this investigation. In the presentation of the data (Figs. 13, 14, and 15) several specimens with medium moisture contents, 60 to 80 per cent saturation, will be noted. Moisture contents in this range resulted from one of the earlier resaturating experiments, i.e., submersion in water for six days. This procedure was found to be unsatisfactory as a rapid means of restoring the materials to uniform 100 per cent saturation.

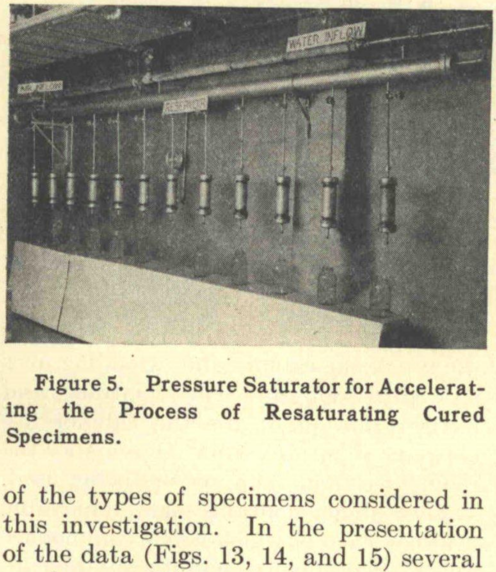


Figure 5. Pressure Saturator for Accelerating the Process of Resaturating Cured Specimens.

The author realizes that a pressure head of 30 lb. per sq. in. is not comparable with any field conditions in highway work. This method and pressure was adopted only for the purpose of accelerating the saturation of the specimens for the wet test group. The possibility of various mixtures of soil and admixtures ever attaining in the field a condition of capillary saturation is another phase of this investigation which is not yet complete.

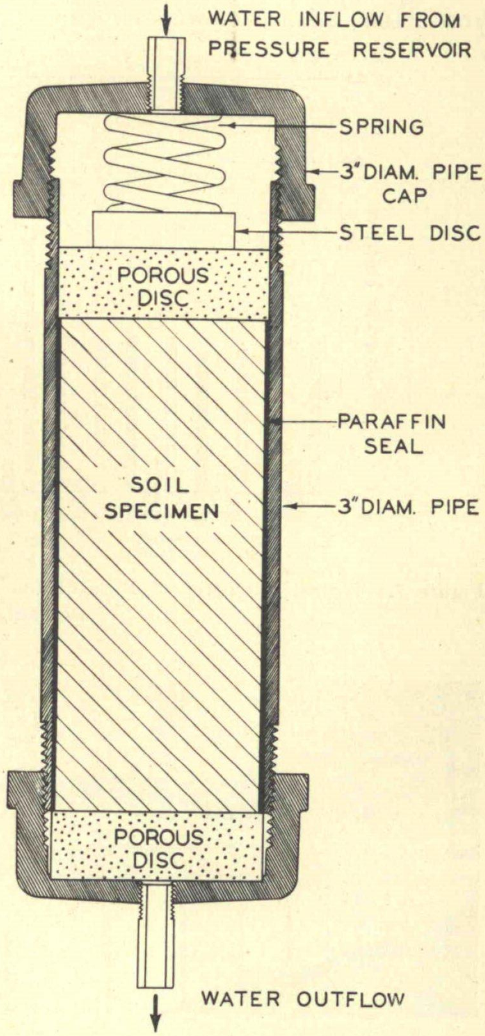


Figure 6. Cross Section of One of the Units of the Pressure Saturator

In Figure 7 are shown the results of resaturation of typical stabilized soil mixtures.

FROST ACTION TEST EQUIPMENT AND PROCEDURE

Refrigeration Equipment. In order to reproduce in the laboratory natural soil freezing conditions, the cold room and frost-action cabinet shown in Figure 8, were designed and constructed, on the basis of the work previously done by Taber, Beskow and Casagrande.

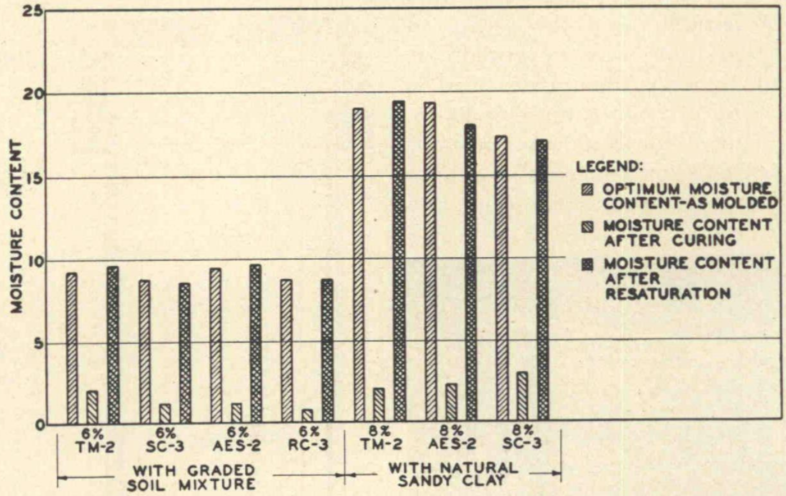


Figure 7. Typical Examples of Resaturation of Cured Bituminous Materials by Means of Pressure Saturator

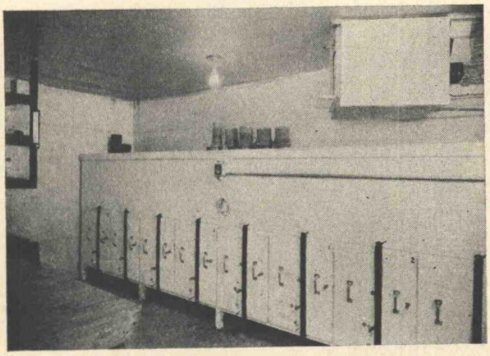


Figure 8. Frost Action Cabinet

The cold room is insulated with 4 in. of cork in walls, ceiling, and floor, measures 9 by 14 ft. inside, has an automatically controlled temperature range of 10° to 70°F., and is cooled by a blower type cooling unit. The frost-action cabinet is insulated throughout with 4 in. of cork, has an automatically controlled temperature range of −20° to 30°F., and is cooled by expansion coils hung from the top of the cabinet and extending over its entire length. The controls and refrigeration plant for the cabinet are entirely separate from those for the room, two freon compressors being used.

The cabinet contains eight removable drawers, each of which will accommodate four test specimens. Ordinarily the cabinet is filled to its capacity of 32 specimens, during a test.

The schematic cross-sectional drawing of one of the cabinet drawers, Figure 9, shows the arrangement of the soil specimens during the test.

This arrangement is essentially similar to that used by Taber (p. 115, reference 5) and Beskow (pp. 51 and 74, reference 8). The side walls of the specimen, which is contained in a paraffin saturated cardboard container, are lubricated with grease, and the entire specimen, with the exception of the top and bottom, is insulated with fine dry sand The freezing temperatures within the frost action cabinet are transmitted to the sample only through its upper surface

To prevent evaporation during the test period, the entire specimen, except for the bottom surface, is sealed with a thin air-tight covering of paraffin A small air vent must be provided in the top surface of the paraffin coating to allow the escape of air displaced by rising capillary water. The card-board containers, made from common one-quart ice cream containers, provide adequate lateral protection for the specimen, while the grease between the paraffin coating of the sample and the card-board container reduces frictional resistance to the vertical movement during frost heaving It was found, however, that, if the freezing cabinet temperature was raised and some of the lower ice layers melted, the frictional resistance was too great to allow the sample to subside under its own weight

The bottom of the specimen rests on a porous carbon disc which, in turn, is carried by the water supply pan in the bottom of the cabinet drawer. The water supply pan is not insulated and the temperature of the water supply, which can feed directly through the porous disc to the soil capillaries and thence to the zone of freezing, is only slightly lower than the temperature of the cold room, that is, approximately 40°F Thus there is a continual flow of heat upward through the sample to the zone of freezing. This condition, on a reduced vertical scale, is comparable to the temperature conditions in the field. At very low temperatures in the freezing cabinet (below 0°F) the loss of heat through the water supply pan and sample usually becomes great enough to freeze the entire sample and occasionally to freeze the water in the supply pan during the last day of the test period

The freezing cabinet drawers, which are removable for placing and removing the specimens and for inspection during the test, are sealed in the freezing cabinet by automobile inner tubes which are inflated during test and deflated for removal of the drawers

Test Procedure The testing procedure followed is a modification of that of preceding investigations, checked by a preliminary study with the equipment and materials previously described Since the first objective was a determination of the relative effects of frost action in various types of stabilized soil road surfaces and bases now in common use, the test procedure was relatively simple as compared with the methods used by the preceding investigators The ground work had been laid by their studies of the effects of type of freezing, rate of freezing, pressure, water availability, size of grains and voids, etc

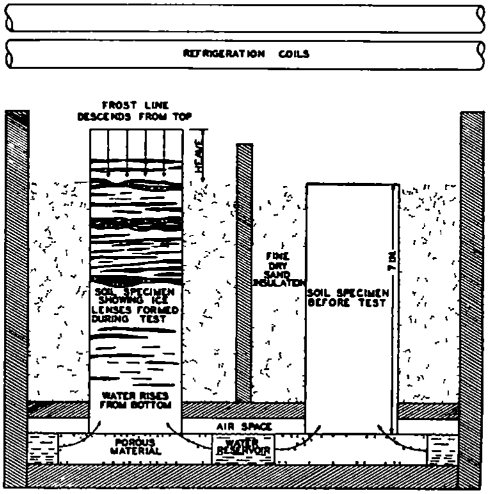


Figure 9. Cross Section of Frost Action Cabinet Drawer Showing Placement of Specimens during Test

All tests were carried out on "open systems," that is, water was always available to the bottom of the specimen. Each test consisted of one slow descent

TABLE 3

Temperature Records and Cumulative Temperature Computations for All Series

Elapsed Time, in Days	Series 2			Series 3			Series 4			Series 5			Series 6			Miscellaneous Temperature Notes
	Air Temp, Deg F	Reduced Temp	Accum Deg Hrs Freeze	Air Temp, Deg F	Reduced Temp	Accum Deg Hrs Freeze	Air Temp, Deg F	Reduced Temp	Accum Deg Hrs Freeze	Air Temp, Deg F	Reduced Temp	Accum Deg Hrs Freeze	Air Temp, Deg F	Reduced Temp	Accum Deg Hrs Freeze	
1	29.5	—	—	28	−1	24	24	−5	120	27	−2	48	28	−1	24	Room temperature was maintained at +40°F throughout the test period
2	29	0	0	27.5	−1.5	60	24	−5	240	25	−4	144	26	−3	96	
3	29	0	0	27.5	−1.5	96	24	−5	360	25	−4	240	26	−3	168	
4	29	0	0	27	−2	144	23	−6	504	25	−4	336	25	−4	264	The water supply temperature gradually dropped from +36°F to +33°F during the test period due to the lowering of the cabinet temperature
5	28	−1	24	27	−2	192	22	−7	672	24	−5	456	25	−4	360	
6	28	−1	48	25	−4	288	21	−8	864	23	−6	600	24	−5	480	
7	27	−2	96	25	−4	384	21	−8	1056	23	−6	744	23	−6	624	
8	26	−3	168	25	−4	480	21	−8	1248	23	−6	888	23	−6	768	
9	25	−4	264	25	−4	576	20	−9	1464	22	−7	1056	22	−7	936	The specimen temperature at the start of the test period was approximately +45°F
10	24	−5	384	24	−5	696	20	−9	1680	21	−8	1248	22	−7	1104	
11	22	−7	552	23	−6	840	19	−10	1920	21	−8	1440	22	−7	1272	
12	21	−8	744	22	−7	1008	18	−11	2184	20	−9	1656	20	−9	1488	Due to periodical starting and stopping of the compressors, the daily maximum and minimum temperatures varied from the daily average by approximately ±1½°F
13	21	−8	936	21	−8	1200	17	−12	2462	19	−10	1896	18	−11	1752	
14	19	−10	1176	20	−9	1416	16	−13	2772	18	−11	2160	18	−11	2016	
15	18	−11	1440	19	−10	1656	15	−14	3120	18	−11	2424	15	−14	2352	
16	17	−12	1728	18	−11	1920	14	−15	3480	16	−13	2736	14	−15	2712	
17	15	−14	2064	16	−13	2232	10	−19	3936	14	−15	3096	13	−16	3096	
18	13	−16	2448	13	−16	2616	5	−24	4512	10	−19	3552	11	−18	3528	Base temperature = 29°F
19	10	−19	2904	30	+1	2592	0	−29	5208	6	−23	4104	8	−21	4032	Reduced temperature = temperature −29
20	0	−29	3600	10	−19	3048				4	−25	4704	2	−27	4680	
21	0	−29	4296	0	−29	3744				0	−29	5400	−5	−34	5496	
22	−10	−39	5232	10	−19	4200				−5	−34	6216	−10	−39	6432	
23				−10	−39	5136				−15	−44	7272				

of the frost line through the entire 7 in of specimen, the temperature in the freezing cabinet being gradually lowered from 30°F to −10°F or −15°F over a period of 21 to 23 days In choosing the length of freezing period and rate of temperature reduction, a careful study was made of the freezing temperatures and critical temperature ranges for all of the types of mixtures to be tested Thus, while many of the clay and graded remix specimens without admixture were completely frozen at 0°F, the freezing temperature for the specimens containing larger percentages of sodium chloride and calcium chloride had not been reached The procedure chosen is a very severe test but is certainly within the limits of natural occurrence in the northern states

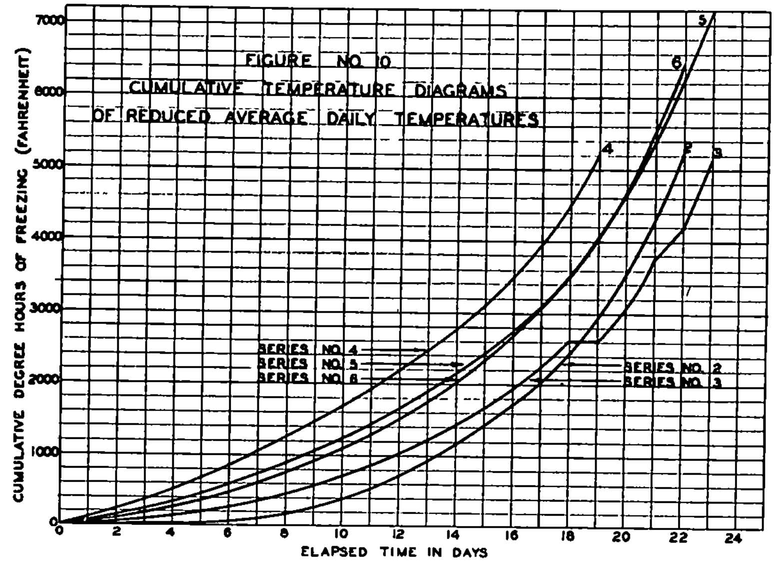


Figure 10 Cumulative Temperature Diagrams of Reduced Average Daily Temperatures

All specimens were tested under very similar conditions of temperature variation and general preparation technique Table 3 outlines the daily temperature variations for five series of frost action tests and other important data on the temperatures of the room, water, and specimen. The reduced temperatures in the freezing cabinet were obtained by subtracting the average daily temperatures from a base temperature of 29°F, temperature values less than 29°F being considered negative The base of 29°F was chosen rather than 32°F to compensate empirically for the initial heat loss between the soil in the specimen and the air temperature in the freezing cabinet The cumulative degree-hours of freezing were computed from the reduced temperatures Figure 10 shows the curves of cumulative degree-hours of freezing plotted against elapsed time of test

COLLECTION OF DATA

A complete record of all details of procedure and test data that may in any way enter into the interpretation and correlation of results has been kept for each specimen

Throughout the investigation, specimens were numbered for identification with three digit numbers The first digit indicated the series or test group of the specimen. Each series of 32 specimens was tested at the same time under identical conditions of temperature variation. The second digit indicates in which of the eight drawers in the freezing cabinet the specimen was placed and the third digit indicates the position in the drawer.

During the test periods, daily readings of the temperatures of the room air, the air immediately above the specimens in each of the drawers, and the water in each of the supply pans, were taken. All temperature readings were made to the nearest degree Fahrenheit with thermometers inserted into the drawers and water pans through small holes provided in the cabinet walls. Since the refrigeration coils extended the entire length of the cabinet, the temperature was within one degree of being the same in all drawers at any one time. One exception was the third position in the eighth drawer. Due to its location, this position lagged about 1°F., and for that reason the "83" specimens in all series have been omitted from the records. For the purposes of this investigation, the temperature variation of one degree in the cabinet has been disregarded and all specimens in any one series are considered to have been exposed to the same conditions of temperature. Thus, only one freezing temperature cumulative curve has been included in the data for each series. (Fig. 10).

A chronological record of the occurrence of frost action was obtained by making daily measurements of the heave of the top of each specimen. Movements were recorded to the nearest 0.02 in., the technique used in making these readings being shown in Figure 11. The rate of heave curves, Figure 20, 21, 22, and 23 show these data, and when correlated with the temperature and photographic records, give valuable information regarding the temperature range for destructive heaving, the time necessary for dry material to attain capillary saturation, the rate of penetration of the frost line, and the freezing point lowering effect of the admixture.

Photographs, which were taken of all specimens within 24 hours after their removal from the frost action cabinet, provide a permanent visual check on the other records. Figure 12 is the photograph of a typical speciman at the com-

Figure 11. Technique of Making Heave Measurements

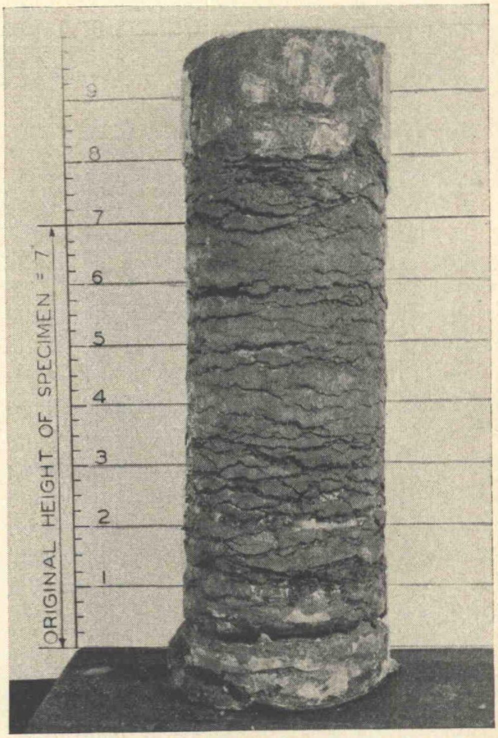


Figure 12. Typical Specimen at Completion of Frost Action Test

pletion of the test. Usually, four specimens of related composition tested in the same drawer were photographed as a group. Visual inspection of the tested specimens is necessary to determine completely the effect of the admixture on the type of frost action, that is on the characteristics of the segregated ice and the sections of the specimen that were affected In the cases of the specimens with a low water content at the beginning of the test, it is possible, by comparing the rate of heave curves and the photographs, to determine exactly when and where in the specimen a state of capillary saturation was reached and ice segregation began. In other cases, the time at which the specimen was completely frozen can be determined.

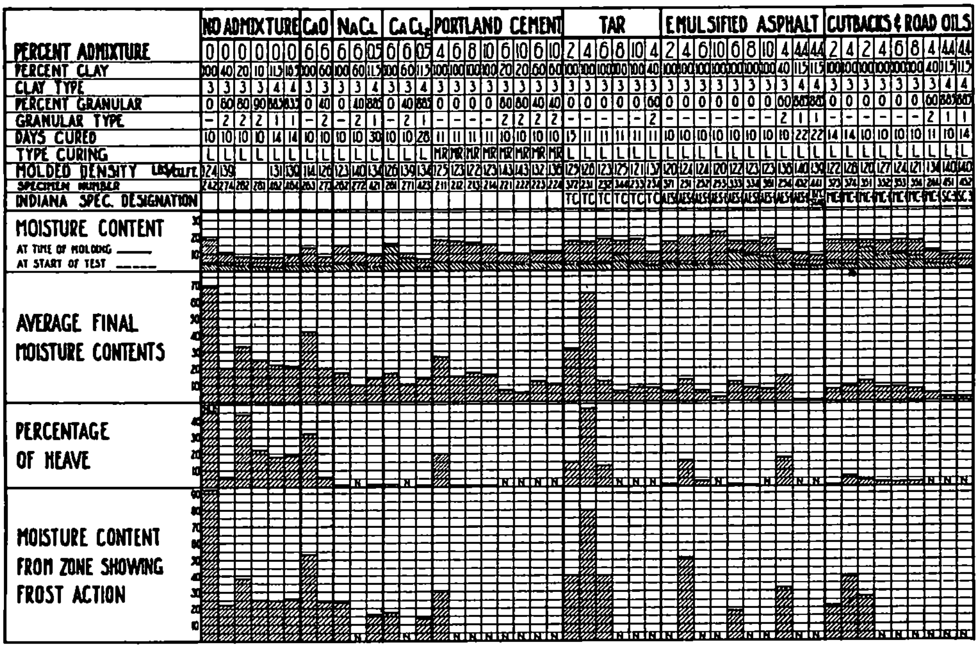
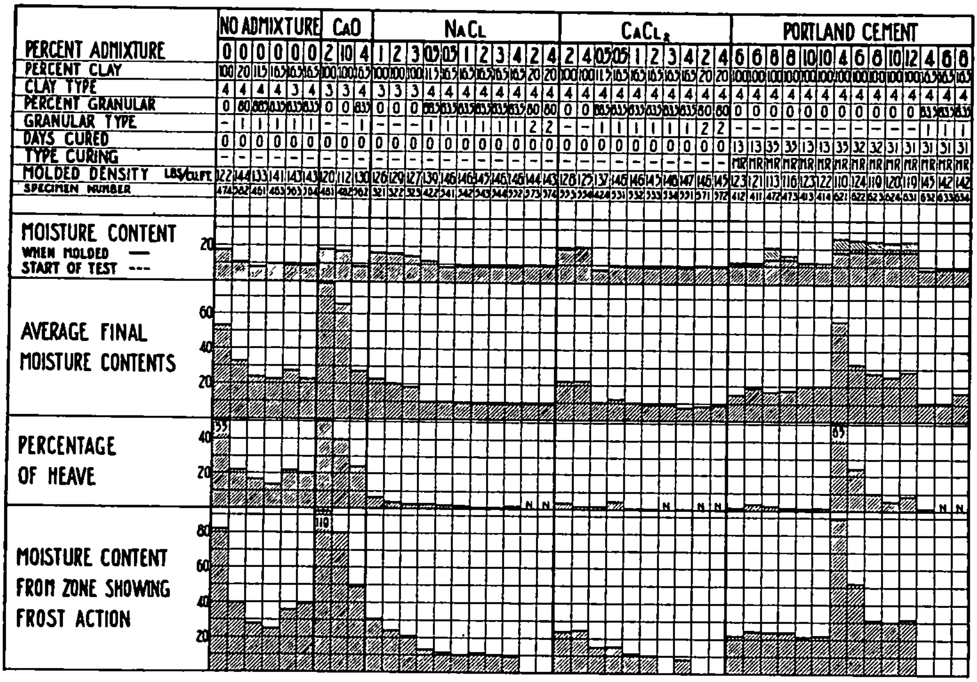


Figure 13 Frost Action Data for Specimens Cured to Low Moisture Content Before Test. Soil Types: 1—Pit Run Gravel 2—Concrete Sand. 3 and 4—Sandy Clay MR, Moist Room; L, Laboratory, N, No Measurable Heave or No Zone of Frost Action. Duplicate Results· 242–243, 264–284; 244–263, 241–364, 213–471, 452–453; 451–454.

The moisture content variation of each specimen was carefully followed from the time of molding until the completion of the test, and moisture contents were computed at the following important stages

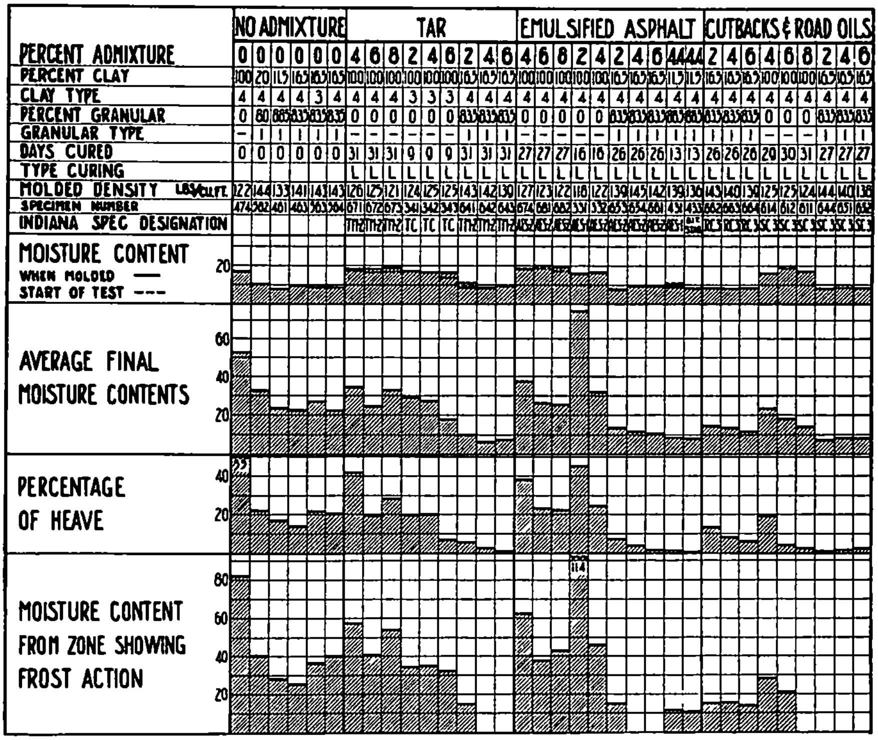
1 When molded
2 At end of curing period
3 Before and after soaking (specimens partially resaturated by immersion).
4 Before and after saturation (specimens resaturated in saturating device)
5 At start of test
6 At completion of test.

At the completion of the test each specimen was cut into representative sections and the moisture content of each section determined by oven drying These final moisture content determinations furnished the data presented in Figure 13, 14 and 15 as "Average Final Moisture Content" and "Moisture Content From Zone Showing Frost Action."



	NO ADMIXTURE						CaO			NaCl											CaCl₂										PORTLAND CEMENT													
PERCENT ADMIXTURE	0	0	0	0	0	0	2	10	4	1	2	3	0.5	0.5	1	2	3	4	2	4	2	4	0.5	0.5	1	2	3	4	2	4	6	6	8	8	10	10	4	6	8	10	12	4	6	8
PERCENT CLAY	100	20	11.5	16.5	16.5	16.5	100	100	16.5	100	100	100	11.5	16.5	16.5	16.5	16.5	16.5	20	20	100	100	11.5	16.5	16.5	16.5	16.5	16.5	20	20	100	100	100	100	100	100	100	100	100	100	100	16.5	16.5	16.5
CLAY TYPE	4	4	4	4	3	4	3	3	4	3	3	3	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
PERCENT GRANULAR	0	80	88.5	83.5	83.5	83.5	0	0	83.5	0	0	0	88.5	83.5	83.5	83.5	83.5	83.5	80	80	0	0	88.5	83.5	83.5	83.5	83.5	83.5	80	80	0	0	0	0	0	0	0	0	0	0	0	83.5	83.5	83.5
GRANULAR TYPE	-	1	1	1	1	1	-	-	1	-	-	-	1	1	1	1	1	1	2	2	-	-	1	1	1	1	1	1	2	2	-	-	-	-	-	-	-	-	-	-	-	1	1	1
DAYS CURED	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	13	13	35	35	13	13	35	32	32	31	31	31	31	31
TYPE CURING	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	MR	MR	MR	MR	MR	MR	MR	MR	MR	MR	MR	MR	MR	MR
MOLDED DENSITY LBS/CU.FT.	122	144	133	141	143	143	120	112	130	126	129	127	139	146	146	145	146	146	144	143	128	125	137	146	146	145	140	147	146	145	123	121	113	116	123	122	110	124	119	120	119	145	142	142
SPECIMEN NUMBER	474	502	461	463	503	504	481	482	562	321	322	323	422	541	542	543	544	552	573	574	553	554	424	531	532	533	534	551	571	572	412	411	472	473	413	414	621	622	623	624	631	632	633	634

Figure 14 Frost Action Data for Specimens Saturated at Start of Test Soil Types· 1—Pit Run Gravel. 2—Concrete Sand 3 and 4—Sandy Clay. MR, Moist Room, L, Laboratory; N, No Measurable Heave Duplicate Results 321–311, 322–312, 323–313; 474–444.



	NO ADMIXTURE						TAR									EMULSIFIED ASPHALT										CUTBACKS & ROAD OILS								
PERCENT ADMIXTURE	0	0	0	0	0	0	4	6	8	2	4	6	2	4	6	4	6	8	2	4	2	4	6	4	4	2	4	6	4	6	8	2	4	6
PERCENT CLAY	100	20	11.5	16.5	16.5	16.5	100	100	100	100	100	100	16.5	16.5	16.5	100	100	100	100	100	16.5	16.5	16.5	11.5	11.5	16.5	16.5	16.5	100	100	100	16.5	16.5	16.5
CLAY TYPE	4	4	4	4	3	4	4	4	4	3	3	3	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
PERCENT GRANULAR	0	80	88.5	83.5	83.5	83.5	0	0	0	0	0	0	83.5	83.5	83.5	0	0	0	0	0	83.5	83.5	83.5	88.5	88.5	83.5	83.5	83.5	0	0	0	83.5	83.5	83.5
GRANULAR TYPE	-	1	1	1	1	1	-	-	-	-	-	-	1	1	1	-	-	-	-	-	1	1	1	1	1	1	1	1	-	-	-	1	1	1
DAYS CURED	0	0	0	0	0	0	31	31	31	9	9	9	31	31	31	27	27	27	16	16	26	26	26	13	13	26	26	26	29	30	31	27	27	27
TYPE CURING							L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L
MOLDED DENSITY LBS/CU.FT.	122	144	133	141	143	143	126	125	121	124	125	125	143	142	130	127	123	122	118	122	139	145	142	139	136	143	140	139	125	125	124	144	140	138
SPECIMEN NUMBER	474	502	461	463	503	504	671	672	673	341	342	343	641	642	643	674	681	682	331	332	653	654	661	431	433	662	663	664	614	612	611	644	651	652
INDIANA SPEC DESIGNATION							TM2	TM2	TM2	TC	TC	TC	TM2	TM2	TM2	AES2	AES2	AES2	AES1	AES2	AES2	AES2	AES2	AES1	[illegible]	RC3	RC3	RC3	SC3	SC3	SC3	SC3	SC3	SC3

Figure 15 Frost Action Data for Specimens Saturated at Start of Test Soil Types: 1—Pit Run Gravel 2—Concrete Sand. 3 and 4—Sandy Clay. MR, Moist Room, L, Laboratory; N, No Measurable Heave. Duplicate Results 474–444, 433–434.

The moisture content determinations other than initial and final, were computed from the difference in weight of specimen at any particular time and the computed oven dry weight

PRESENTATION OF DATA

The data accumulated to date, have been assembled in the form of charts and curves for rapid study and appraisal It is felt that these charts and curves are, for the most part, self-explanatory and a detailed discussion of them is not necessary Significant trends in the data as they relate to effects of soil gradation, type and percentage of admixture, and initial moisture content, will be discussed

Data Charts The vital test data for all specimens have been summarized in tabular and graph form in Figures 13, 14, and 15 The percentage of heave is the ratio of the increase in height of specimen during the test to the original height.

Figure 13 presents the data for the dry test group, which, regardless of whether the materials required curing or not, were cured to low moisture content and tested in that condition, as part of the study of the effects of initial moisture content With few exceptions, all of these specimens had an initial moisture content of 3 to 5 per cent, or about as dry as such materials would ever be found in the field The higher moisture contents of the calcium chloride mixtures were due to the hygroscopic properties of the admixture, and the medium moisture content bituminous mixtures resulted from an earlier resaturating experiment, six days immersion, which was only partially effective

The data in Figure 14 are for specimens from the wet test group, which, with the exception of the portland cement mixtures, were tested at optimum moisture content with no curing The portland cement specimens were cured in a moist closet and then the moisture was restored before the test The first six specimens in the cement mixture group were molded in the field from material taken from the Joint Highway Research Project test road during construction The 6 and 10 per cent mixtures were mixed in place with a rototiller while the 8 per cent mixture was mixed in a concrete mixer, which accounts for the variable densities shown All of the six were resaturated by immersion in water in the laboratory after the curing period in the moist closet The remainder of the cement mixture group was molded in the laboratory and after curing was put through the pressure saturator, accounting for the very high initial moisture contents shown

The data in Figure 15 are for the bituminous mixtures in the wet test group, all of which were molded at optimum moisture content, cured for at least 10 days in the laboratory, and then resaturated in the pressure saturator before the test The "No Admixture" groups are identical on Figures 14 and 15 this repetition being for aid in studying the influence of the admixtures

Probably the most obvious trend in the data presented on the three charts is the correlation between moisture content and frost action As pointed out before, a moisture content of at least capillary saturation is necessary for ice segregation to cccur and, where ice segregation has occurred, the resulting moisture content will be very high These observations are verified definitely by the data on the charts, average final water content and water content for zone at frost action indicating very closely the trend of the percentage of heave

Although the percentage-of-heave indicates, in general, the extent to which frost action may be expected to occur in the various mixtures, the writer does not feel that it can be taken as a basis for rigid comparison of the mixtures As an example, if one mixture shows a heave of 40 per cent and another a heave of 20 per cent, there is not sufficient evidence to conclude that the latter is twice as resistant to frost damage as the former. The important conclusion in such a case is that both mixtures are liable to serious frost damage, the exact extent being entirely dependent upon the conditions of initial moisture content, density and temperature, a variation of any one of which might result in a definite change in the relative amounts of damage.

The percentage-of-heave data can, however, be used as a basis for a general grouping of the various materials as to whether they are resistant or non-resistant to frost action, and if non-resistant, under what conditions the damage will occur. Such a group classification is made later.

The influence of the individual admixtures on the reduction of frost action is evident from the data charts, the general indication being that the protection furnished is directly proportional to the percentage of admixture. Calcium oxide in the percentages tested, (up to 10 per cent) seems to reduce the damage only slightly, certainly not enough to justify its use for this particular purpose. Calcium chloride and sodium chloride definitely reduce frost action because of their freezing point lowering effect. The tests indicate that as long as the chemical is present in the soil, 2 or 3 per cent of calcium chloride or sodium chloride will reduce frost damage to a minimum by preventing freezing at −10 to −15°F. The permanency of admixtures of this type is one of the items that has not been completely investigated. An interesting observation, however, is that specimens containing only a small percentage of chemical, 2 per cent or less, froze and were slightly damaged in the bottom 1 to 3 in. of material. This may indicate that the rising capillary water carried with it most of the chemical from the lower part of the specimen, or that the chemical is readily carried through the soil by permeating water.

The effects of portland cement and the various bituminous admixtures appear to be not only directly proportional to percentage of admixture, but to depend to a large extent upon the amount of water available in the material at the start of the freezing period. As an example, it will be seen, referring to the charts, that 8 per cent cement, tar, emulsified asphalt, or cutback asphalt reduced frost damage to a minimum in the dry test group, but when these same materials were tested with a high initial moisture content, serious frost damage occurred.

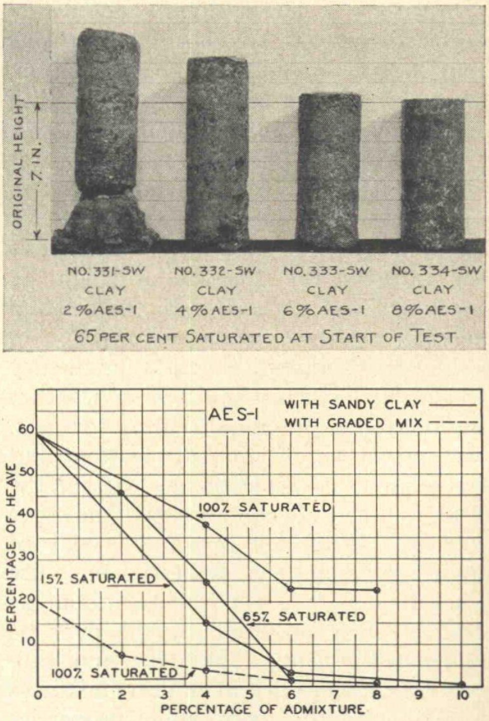


Figure 16. Effects of Admixture and Initial Moisture Content—Emulsified Asphalt

Effect of Admixture and Moisture Content Curves. The test data for all of the specimens embodying one particular type of admixture are presented by means of Figures 16, 17, 18, and 19. Specimens tested in the same series and with similar initial moisture contents provide the data for one curve.

In interpreting the data on these curves, as well as elsewhere in this paper, heaves of 5 per cent or less should not be considered indicative of serious damage.

The photograph accompanying each set of curves shows the final condition of the tested specimens represented by one of the curves. The specimens in Figures 16 and 17 were photographed after the paraffin seal coat had been removed, while those in Figures 18 and 19 were photographed before removal of the paraffin.

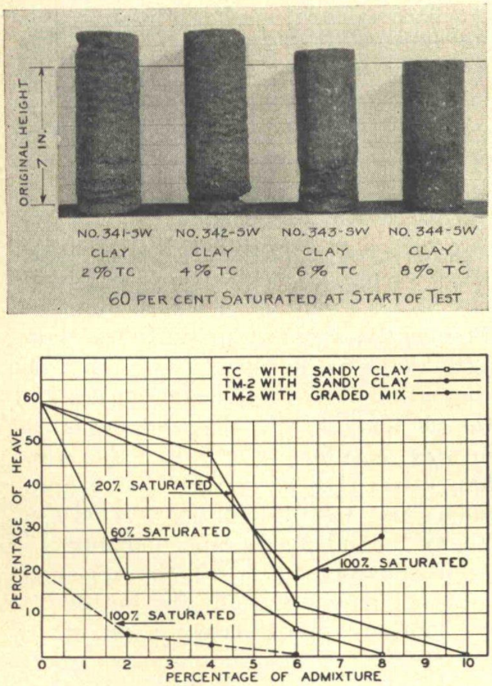


Figure 17. Effects of Admixture and Initial Moisture Content—Tar

In general, the moisture remaining in a specimen after the curing period is equivalent to 15 to 30 per cent saturation in terms of the water required to fill all the voids of the soil. Specimens which were immersed for six days before being tested reached 50 to 70 per cent saturation. Specimens put through the pressure saturator reached, with few exceptions, 100 per cent saturation.

These data again show that the influence of any particular percentage of admixture is directly dependent upon the moisture content of the mixture at the start of the freezing period, and conclusions concerning the percentage of admixture required to prevent frost damage can be made only when the limiting conditions of initial moisture content are included.

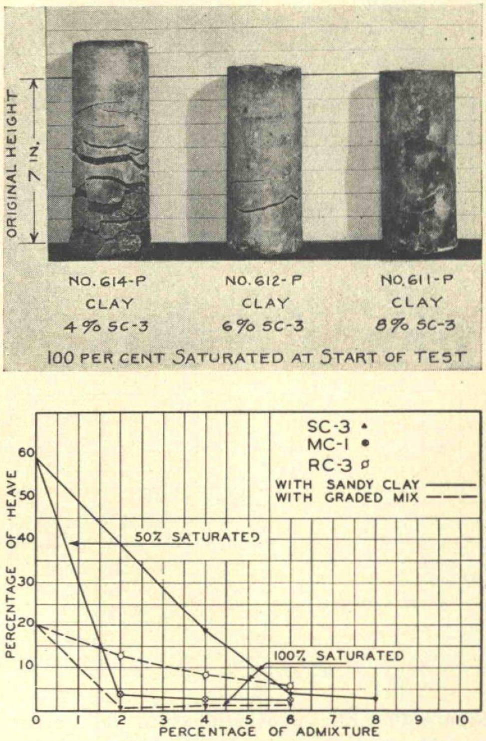
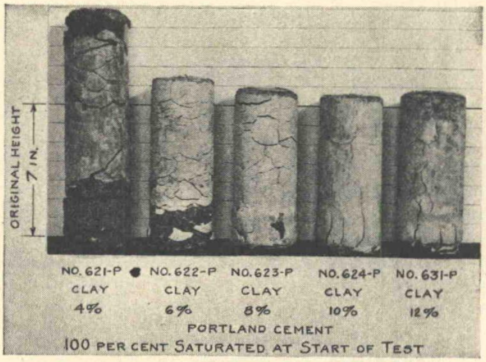


Figure 18. Effects of Admixture and Initial Moisture Content—Cutbacks and Road Oil

At this time it is impossible to say whether the irregularities in the data for the tar group are due to errors or are actually indicative of the characteristics of the admixture.

The definite reduction of frost action resulting from the addition of granular material is evident from these data. All of the data indicate that frost action is much more readily controlled in graded mixtures than in natural fine grained soils, which verifies the findings of other investigators that grain diameter distribution is of fundamental importance in the frost action process.

Rate-of-Heave Curves. The rate-of-heave curves shown in Figures 20, 21, 22, and 23 present a chronological record of the occurrence of frost action in those specimens from each of Series 2, 3, 4 and 6, respectively, in which damaging frost action occurred. The daily heave measurements (Fig. 11) furnished the data for the rate-of-heave curves, and the daily temperature readings (Table 3) furnished the data for the cumulative temperature diagram accompanying each set of curves.



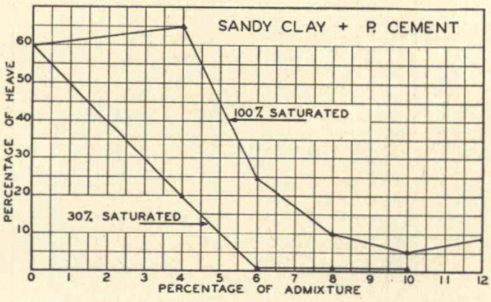


Figure 19. Effects of Admixture and Initial Moisture Content—Portland Cement

In general, the specimens of natural sandy clay started to heave sooner, heaved at a greater rate, and reached a greater total heave than did the stabilized soil mixtures. The rate-of-heave was less influenced by stabilization than were the other two items.

The degree to which the admixture inhibited capillary flow in the soil is indicated by the length of the period of inactivity before heaving started. Referring to Figure 20, it is evident that capillary saturation in most of the bituminous specimens was delayed until the fourteenth day or later. However, when the frost line finally did penetrate into that portion of the specimen which was saturated by capillarity, frost action resulted in heaving at a rate that was only slightly less than the rates of the untreated soils. Specimens No. 251 and No. 232 are good examples of the delayed start typical of bituminous mixtures having low initial moisture content. Frequently, a tested specimen was damaged only in the lower 2 to 3 in. By comparing the rate-of-heave curves and the photographs of the tested specimens it was possible to tell exactly what happened. For example, refer to Specimen No. 343, rate-of-heave curve in Figure 21 and photograph in Figure 17. Approximately $5\frac{3}{4}$ in. of the specimen were not damaged while the bottom $1\frac{1}{4}$ in. contain approximately $\frac{3}{4}$ in. of ice lenses. Correlating the data from both sources, it can be concluded that during the first 16 days of the test period the frost line penetrated $5\frac{3}{4}$ in. and the capillary saturation line rose $1\frac{1}{4}$ in. On the sixteenth day the two met and the ice segregation began.

Figure 22 brings out clearly the effect on rate and total heave of the addition of granular material to the mixture. The data indicate that the frost line penetrates the graded mixtures much more rapidly than it does the natural fine grained soils with the result that the total damage is less in the graded mixture. Apparently most of the damage was done in the graded mixtures during the first 8 to 10 days, while the natural soils continued to heave at a fairly uniform rate during the entire test period It must be remembered, however, that, for a given freezing period, thicker layers of graded mixture and natural fine-grained soils might show equal amounts of damage although the depths of frost penetration would be very different This set of curves also shows the effect of more rapid accumulation of degree-hours of freezing The temperature of the freezing cabinet was lowered more rapidly at the start of the test period for this series than for the others, with the result that most of the specimens started heaving almost immediately, in contrast to the more delayed start accompanying the slower temperature reduction in the other series.

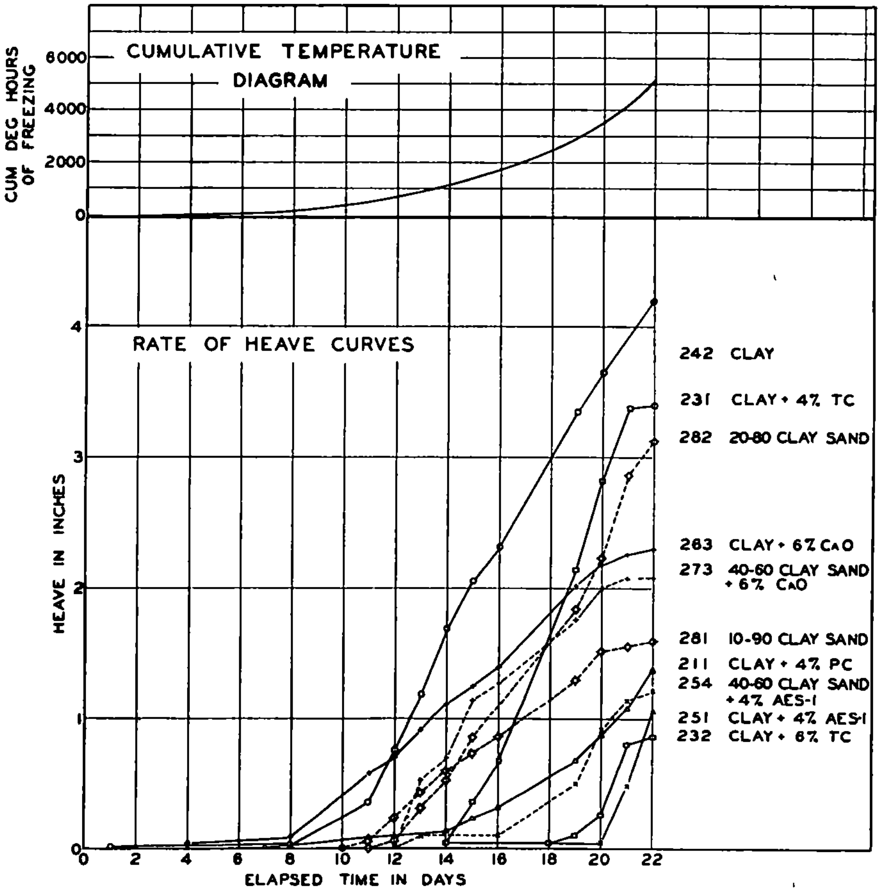


Figure 20. Rate-of-heave, Series 2

The data for Series No 6, Figure 23, furnished the best means of comparing the influence of the various admixtures on rate of heave All of the specimens in this group were 100 per cent saturated at the beginning of the freezing period and all were made with natural soil plus admixture, no graded soil mixtures being included The variations in behavior are therefore primarily due to the admixtures.

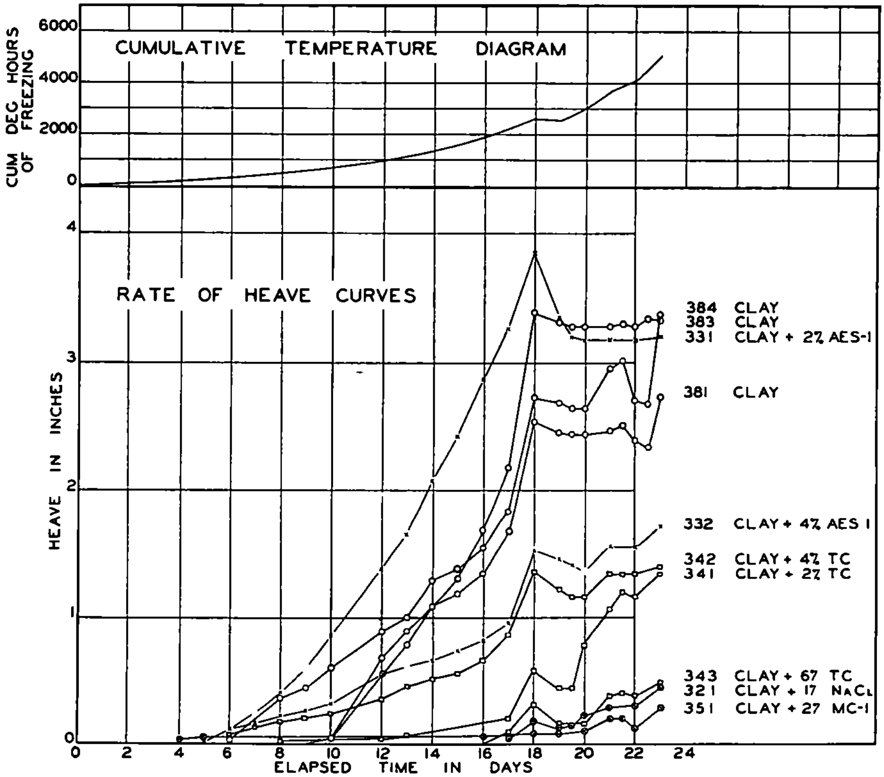


Figure 21 Rate-of-heave, Series 3

CONCLUSIONS

A review of the limitations affecting the conclusions that have been drawn seems appropriate at this point.

Early in the paper it was shown, based on the work of previous investigators, that the following conditions are necessary for the occurrence of ice segregation and frost heaving in soils

1. Capillary saturation of the soil at the beginning or during the freezing process
2. A free supply of water from within or without the soil
3. A minimum percentage (3 to 10) of grains smaller than 0.02 mm.
4. A gradual decrease in temperature of the air above the soil to below freezing temperature.

Condition 3 is satisfied by the grain diameter distribution of most stabilized soil mixtures. Conditions 2 and 4 were provided for in the design of the freezing cabinet Condition 1 was satisfied artificially for part of the specimens prior to the test period by means of the pressure saturator, and all specimens were exposed to the necessary conditions for naturally attaining capillary saturation during the test period by placing their bottom surfaces in a free water supply.

With one exception of some of the initial moisture content conditions which require further study, the test conditions are believed to be reasonably within the limits of those that might be expected in the field

Only one soil type has been used in preparing the test specimens. This was, however, fairly typical of soils used in stabilization in which serious frost action does occur

Conclusions in regard to percentages of admixture are based strictly upon the results of those percentages actually investigated. No interpolations are made.

With the foregoing limitations in mind, the author has used the evidence presented in this paper to draw the following conclusions

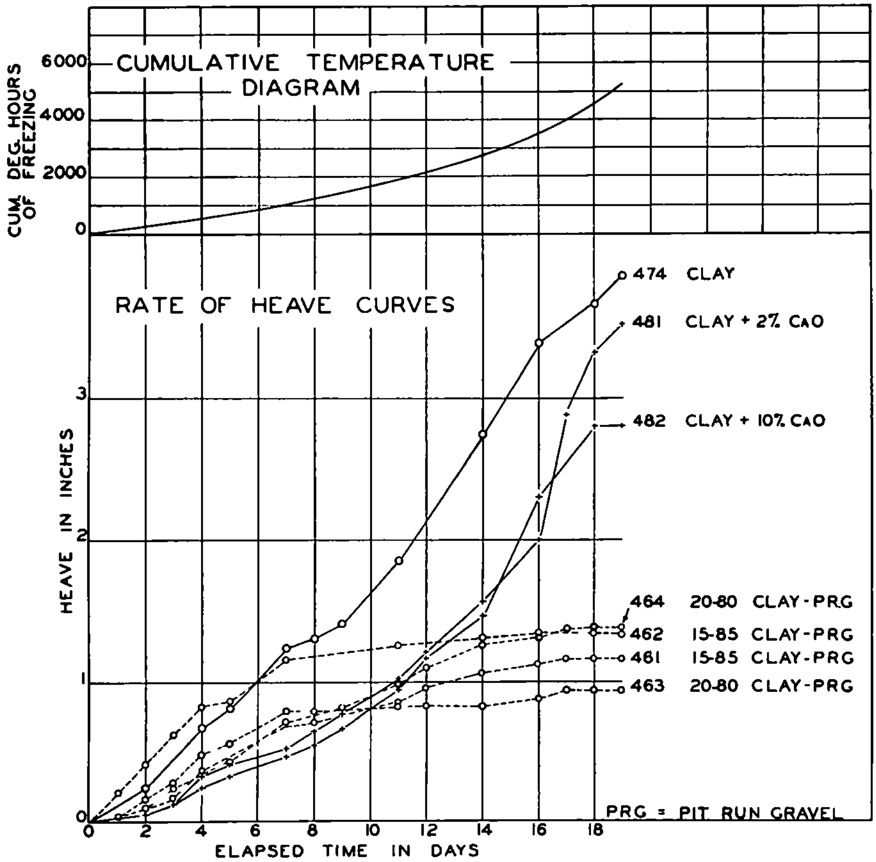


Figure 22. Rate-of-heave, Series 4

Of the seven requirements of a good stabilized soil road outlined at the beginning of the paper, only one, resistance to frost action in stabilized surface or base, has been considered in this investigation. The data are not intended to be applicable to the problem of frost heaving due to ice segregation in the subgrade.

GENERAL

1 Many of the types of stabilized soil mixtures now in common use are liable to serious damage by ice segregation, retarded to various degrees by the

stabilization process, but occurring just as it does in natural soils

2 Decisions as to the extent to which frost damage may be expected to occur in a stabilized soil mixture can be made only when the limiting conditions of initial and attainable moisture content are known

3 In general, natural fine grained soils start to heave sooner, heave at a greater rate, and reach a greater total heave than do stabilized soil mixtures exposed to the same conditions

4 Once capillary saturation is reached and ice segregation begins in a stabilized soil mixture, the rate of heaving is usually only slightly less than for natural soils

5 When a treated soil mixture begins the test at a low moisture content, the degree to which the admixture waterproofs the soil is directly proportional to the length of the period of inactivity before heaving starts

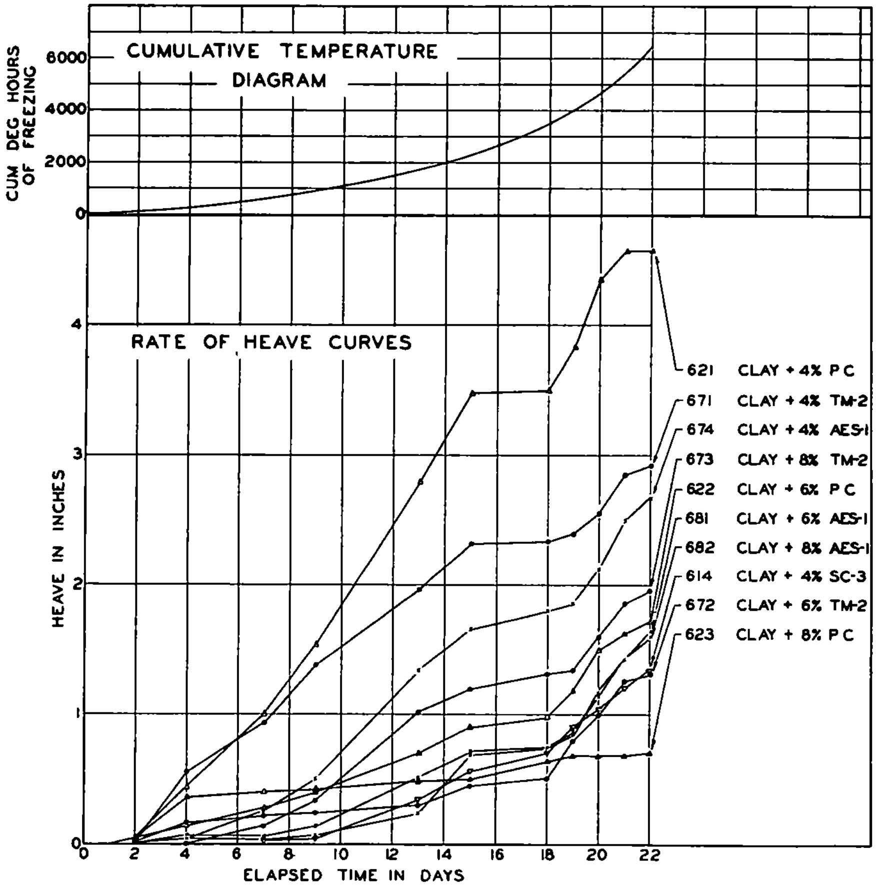


Figure 23. Rate-of-heave, Series 6

6 The available data indicate that the frost line probably penetrates a well graded mixture at a greater rate than it does a natural fine grained soil, resulting in less total damage to the former but approximately the same rate of heaving for both

7 Percentage-of-heave data are not

sufficiently constant to be used as a criterion for rigid comparison of stabilized soil mixtures, but should be used only as a means of general classification of the mixtures into heaving and non-heaving groups

8 Any of the types of stabilized soil mixtures included in this investigation can be saturated by a pressure of 30 lb per sq in applied for 24 hours or less

REGARDING ADMIXTURES

9 All of the admixtures tested are much more effective in reducing frost action when used with well graded soil mixtures than when used with natural fine-grained soils

10 Calcium oxide (2, 6, 10 per cent, natural soil, 4 per cent, graded soil mixture)[1] does not increase the mixtures resistance to frost action enough to warrant its use for this purpose The mixtures take on water readily and, provided water is available for capillarity, the degree of saturation at the beginning of the freezing period is of little consequence

11 Sodium chloride (natural soil plus 1, 2, 3, 6 per cent, graded soil mixture plus ½, 1, 2, 3, 4 per cent) and calcium chloride (natural soil plus 2, 4 per cent, graded soil mixture plus ½, 1, 2, 3, 4 per cent) provide good resistance to frost action primarily because of the freezing point lowering effect of the admixture The data indicate that as long as the soil retains the chemical in its full concentration, 2 to 3 per cent chemical prevents freezing at −10 to −15°F and thereby prevents frost damage

12 The resistance to frost action of a soil cement mixture (natural soil plus 4, 6, 8, 10, 12 per cent, graded soil mixture plus 4, 6, 8, 10 per cent) is directly proportional to the percentage of cement and the degree of saturation of the mixture at the beginning of the freezing period. See No 14 for details

13 In general, the resistance to frost action of bituminous mixtures is directly proportional to the percentage of admixture and the degree of saturation at the beginning of the freezing period When 100 per cent saturated, serious frost damage will occur in any of the types of natural soil plus bitumen mixtures tested, up to 8 per cent admixture More definite conclusions for use in forecasting frost damage in the bituminous mixtures cannot be drawn until the study of field moisture contents is completed

14 Based on the data presented, the following group classifications can be made

Group No 1, damaged by frost action at all percentages of initial moisture content.
  Sandy clay (natural)
  Graded mixtures of clay plus gravel and clay plus sand
  Sandy clay plus 2, 6, 10 per cent CaO
  Graded soil mixture plus 4, 6 per cent CaO
  Sandy clay plus 1 per cent NaCl
  Sandy clay plus 1 per cent $CaCl_2$
  Graded soil mixture plus ½ per cent $CaCl_2$
  Sandy clay plus 4 per cent portland cement
  Sandy clay plus 2, 4, 6 per cent TC
  Sandy clay plus 2, 4 per cent AES-1
  Sandy clay plus 2, 4 per cent MC-1
Group No 2, Damaged only when initial moisture content was approximately 100 per cent saturation
  Sandy clay plus 6, 8, 10, 12 per cent portland cement
  Sandy clay plus 4, 5, 8 per cent TM-2
  Sandy clay plus 4, 6, 8 per cent AES-1
  Sandy clay plus 4 per cent SC-3
  Graded soil mixture plus 2 per cent AES-1
  Graded soil mixture plus 2, 4, 6 per cent RC-3
Group No 3, no frost damage at all degrees of initial moisture content
  Sandy clay plus 3, 4, 6 per cent NaCl
  Graded soil mixture plus ½, 2, 4, 6 per cent NaCl
  Sand clay plus 3, 4, 6 per cent $CaCl_2$
  Graded soil mixture plus 2, 4 per cent $CaCl_2$
  Graded soil mixture plus 4, 6, 8 per cent portland cement
  Graded soil mixture plus 4, 6 per cent TM-2
  Graded soil mixture plus 4, 6 per cent AES-1
  Graded soil mixture plus 4 4 per cent Bitumils Stabilizer
  Sandy clay plus 6, 8 per cent SC-3
  Graded soil mixture plus 2, 4, 6 per cent SC-3

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[1] Percentages investigated

ACKNOWLEDGMENTS

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DISCUSSION ON FROST ACTION

Mr. J. C Roediger, *Standard Oil Development Company:* Has any test been made to determine volume increase and not just ice increase?

Mr. Winn With the occurrence of frost action, the ice forms in horizontal lenses and therefore all the movement is vertical We measure the rise in the body of the surface It does not move laterally at all.

Mr. A. F. Gill, *National Research Council of Canada:* Was the percentage of chemical based on the weight of dry soil or on the weight of moisture present?

Mr Winn. It was based on the weight of dry soil.

Mr Gill. You mentioned a figure of 2 or 3 per cent, would that vary considerably with the sieve analysis of the material?

Mr. Winn. Yes