FROST BEHAVIOR OF COMPACTED SOILS

Mian-Chang Wang, University of Rhode Island; and
Gilbert L. Roderick, University of Wisconsin

The frost behavior of compacted soils subjected to a unidirectional penetration of freezing temperature from the top under a temperature gradient of 20 F/6 in. was studied. The results indicated that rate and maximum depth of freezing temperature penetration, water content increase, frost heave, and development of ice segregation were dependent greatly on soil texture compositions and compaction conditions including initial degree of saturation, molding moisture content, and dry density. Although sand size content was constant, increasing the clay size content (smaller than 0.002 mm) decreased frost heave, average water content increase, size of ice lenses, and depth to ice front. In general, decreasing the dry density only decreased the rate of frost penetration and increased the amount of water content increase and total heave. However, frost heave of Providence silt compacted by using standard AASHO compaction increased as molding moisture content increased regardless of the change in dry density. Frost heave increased linearly with average water content increase. The rate of increase, for a constant degree of saturation, increased as percentage of fines decreased.

●FREEZING causes volume to increase in soils because of volume expansion of interstitial water and formation of ice lenses in the soils. Frost heaving in soils may result in engineering problems and failures in hydraulic structures, highway pavements, and buildings. Because of the detrimental effects of frost action, considerable progress has been made in clarifying the mechanism of frost action in soils (1-7), in understanding the factors affecting frost action (8-13), and in developing techniques for handling frost-susceptible soils (13-16).

Frost action is a dynamic unsteady-state process, the nature of which is complex and involves a number of variables that are strongly interrelated. Because the intensity of frost action depends on so many factors that are indeterminate, it is almost impossible to predict the amount of frost heave in a soil under field conditions by means of laboratory tests and available theory. However, the relative potential for frost heave to occur in any soil could be estimated by studying the various factors that aid in its development.

This study was, therefore, undertaken to investigate the effect of a number of factors, such as molding moisture content, initial degree of saturation, dry density, and soil texture, on the frost behavior of compacted soils. The frost behavior that was studied included depth and rate of frost penetration, moisture migration due to freezing, frost heaving, and development of ice segregation.

APPARATUS, MATERIALS, AND TEST PROCEDURE

Tests were conducted by measuring temperature, overall heave, and final moisture content and by observing the development of ice segregation in test specimens subjected to a unidirectional penetration of freezing temperature under a temperature gradient of 25 F at the top and 45 F at the bottom of the 6-in. high test specimens. The testing

---

Sponsored by Committee on Frost Action and presented at the 50th Annual Meeting.

apparatus included a cold chest, a galvanometer and thermocouples, dial gages, and an X-ray machine. A detailed description of the apparatus is given in the Appendix; a schematic view of the test setup is shown in Figure 1.

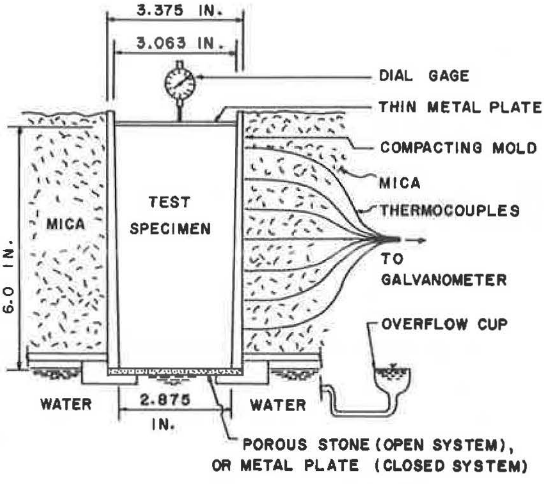

Figure 1. Schematic view of test setup.

Five soil specimens were tested simultaneously. Overall heave and final moisture content were determined for all test specimens. Soil temperature readings were taken only from the specimen located at the center of the group, and observation of ice segregation was made only for the specimen located at the front left side.

Three test soils were used: Providence silt and 2 mixtures of Providence silt with different amounts of commercial Ca-montmorillonite plus sand-sized particles. One mixture had 21 percent Ca-montmorillonite plus 4 percent sand, and the other had 57 percent Ca-montmorillonite plus 10 percent sand by weight. The index properties of the 3 test soils are given in Table 1; the distribution of grain sizes are shown in Figure 2.

Test specimens were compacted by using a drop-weight compaction machine manufactured by Soiltest, Inc. The device had a drop weight of 15 lb for striking the top piston of the compaction mold. The drop height for the weight was controlled by a clip arrangement on the shaft guide.

The compaction molds, having inside diameters of 2.875 in. at the bottom and 3.063 in. at the top and a height of 6 in., were made of 2-5/6 in. (inside diameter) by 1/4 in. thick Lucite cylinders. The reason for using inside-tapered cylinders was to reduce wall friction or resistance to heaving. Damage due to compaction was prevented by confining the Lucite cylinder in a steel mold having an inside diameter exactly equal to the outside dimension of the Lucite cylinder.

The test specimens were compacted in 3 equal layers. Without the soil specimen being extruded from the Lucite mold, the specimen was capped with aluminum foil to prevent moisture evaporation and was then installed in the test chamber for at least 24 hours. Temperature in the test chamber at this stage was controlled at 45 F for the purpose of simulating field ground temperature.

Immediately following installation of the thermal insulation system and the heave- and temperature-measuring systems, testing was started by regulating the temperature

TABLE 1

INDEX PROPERTIES OF TEST SOILS

Test		Specific Gravity	Liquid Limit	Plastic Limit (%)	Plasticity Index	Texture Composition[a]		
Number	Soil					Clay (%)	Silt (%)	Sand (%)
1	Providence silt	2.75	28.0	24.0	4.0	9	54	37
2	Providence silt + 21% Ca-montmorillonite + 4% sand	2.74	35.2	24.5	10.7	13	50	37
3	Providence silt + 57% Ca-montmorillonite + 10% sand	2.71	46.8	26.0	20.8	23	40	37

[a] According to International Society of Soil Science Classification System: clay size, < 0.002 mm; silt size, 0.002 to 0.02 mm; sand size, 0.02 to 2.0 mm.

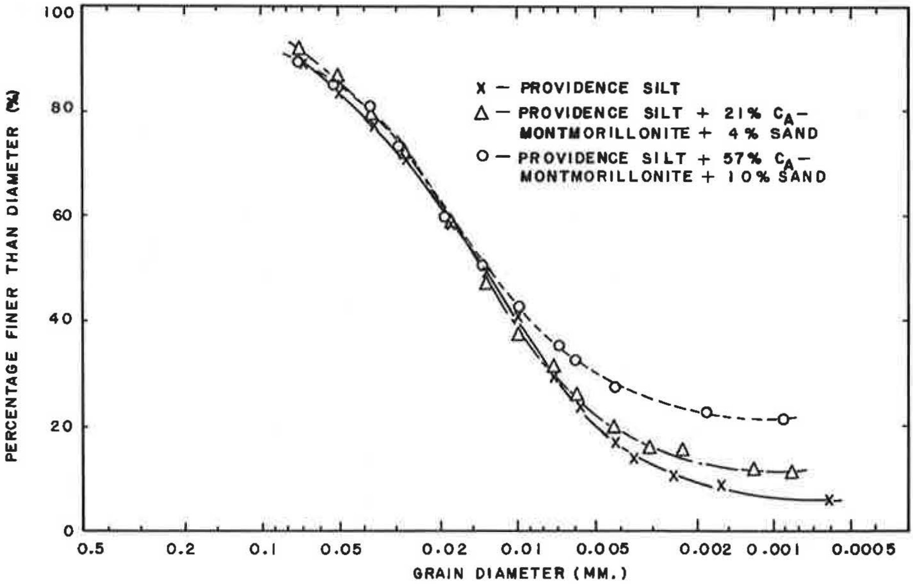

Figure 2. Distribution of grain sizes in soils investigated.

at the top of the test specimens to 25 F and by keeping the temperature at the bottom of test specimens constant at 45 F. Both 25 F and 45 F temperatures were used respectively at the top and the bottom of the test specimens throughout all tests. During testing, soil temperature readings were taken at total elapsed time intervals, such as 1, 2, 3, 5, 7, 15, and 30 hours, whereas overall heave determination and ice segregation observations were made every 24 hours. All tests were terminated after 5 days.

EXPERIMENTAL RESULTS AND DISCUSSION

Soil Temperature

Because of the unidirectional penetration of subfreezing temperature from the top of the test specimens, soil temperature at a certain depth decreases with increasing time of freezing. Typical curves for the variation of the soil temperature at different depths with freezing time for the compacted Providence silt in both closed and open systems are shown in Figures 3 and 4 respectively. It is seen that the slopes of the curves decrease as freezing time increases, implying that the soil temperature at any depth drops at a rate that decreases as freezing time increases because of the decreasing temperature gradient associated with increasing freezing time. In addition, because the curves are nearly parallel to each other, the rate of soil temperature change is nearly independent of the depth. The supply of excess water from the bottom of the test specimens in the open system causes a slower rate of cooling in the open system than in the closed system, as shown in Figure 5.

Effect of dry density on the rate of freezing temperature penetration, under a degree of saturation of 60 percent, is shown in Figure 6. Figure 6 also shows the following:

1. The effect of dry density was insignificant in the closed system; in the open system, the higher the dry density was, the deeper the freezing temperature penetration was.
2. At early stages of freezing, the rate of freezing temperature penetration in the open system was nearly a constant regardless of the magnitude of dry density; the rate in the open system was slower than that in the closed system because of the effect of additional water supply.

During the freezing process, the only sources of heat supply were moisture transport and the latent heat of fusion of the water in the soil. The moisture transport is

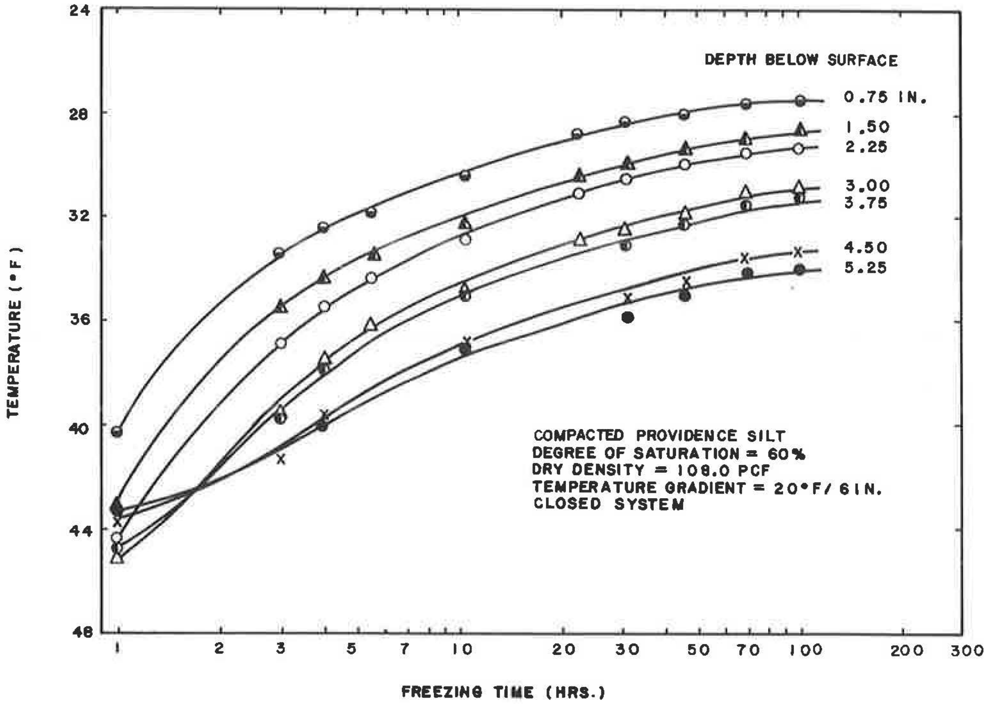

Figure 3. Variation of temperature at different depths with freezing time for Providence silt in closed system.

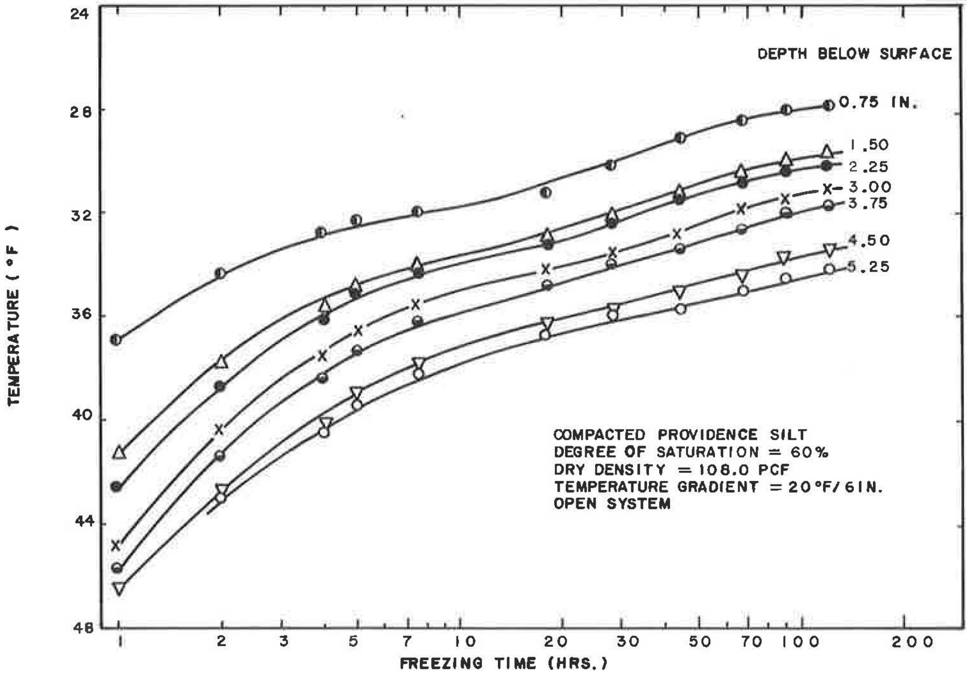

Figure 4. Variation of temperature at different depths with freezing time for Providence silt in open system.

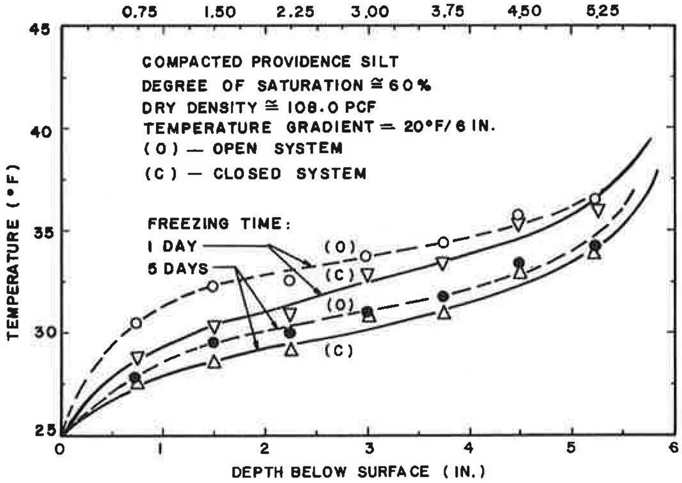

Figure 5. Soil temperature distribution with depth.

caused by the pressure deficiency at the ice front. The pressure deficiency is a measure of the matrix and osmotic potentials. Because the variation of osmotic potential for the conditions under study is generally considered to be negligible (17), the pressure deficiency reflects essentially the matrix potential. The matrix potential is a function of water content, and change in water content is directly influenced by the rate of ice lens growth that, in turn, is controlled by the external temperature gradient and the physical properties of the soil. For a given external temperature gradient,

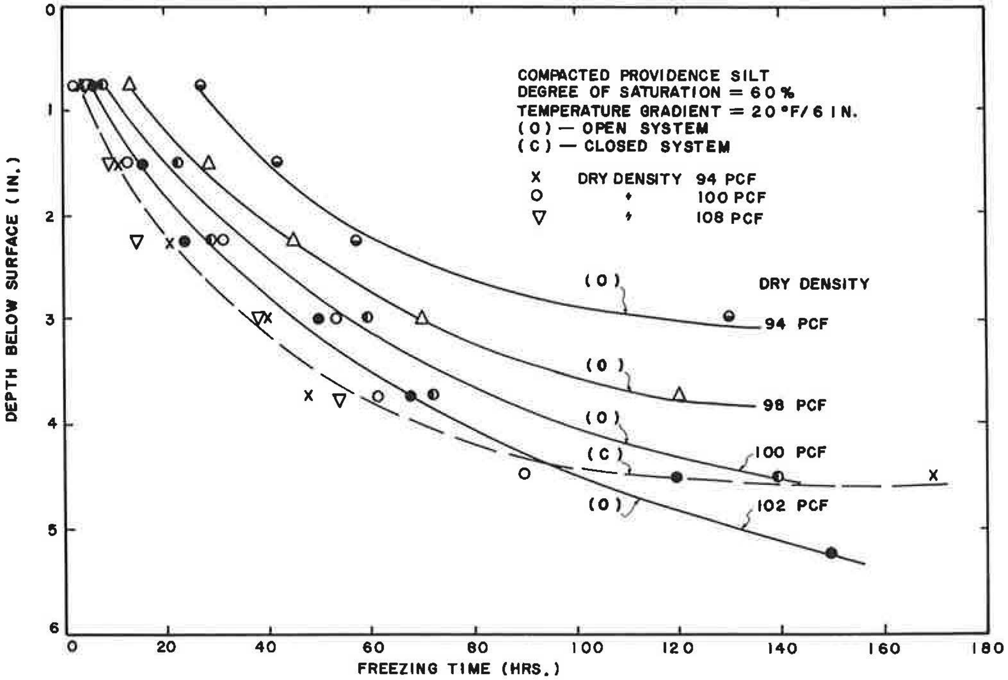

Figure 6. Penetration of 32 F temperature as a function of freezing time for a constant degree of saturation in both open and closed systems.

therefore, the pressure gradient would be directly related to the physical properties of the soil including the composition of the soil and the state of the soil mass with regard to soil moisture content, density, and the like. According to Darcy's law, the amount of water flow is directly proportional to the soil permeability and the pressure gradient. It follows that the soil property is the only essential factor controlling the amount of moisture transfer, as long as the external temperature gradient is a constant. For a constant degree of saturation, a lower dry density results in a higher void ratio and leads to a higher amount of moisture transfer. Consequently, a lower dry density gives a larger amount of moisture transfer to raise the soil temperature and impede the penetration of freezing temperature.

Latent heat depends only on the amount of water in a unit volume of soil. The lower the dry density is, under a constant degree of saturation, the higher the amount of water in a unit volume of soil will be, and, accordingly, the higher the latent heat will be. From the combination of these 2 effects (i.e., a large amount of moisture transport and a high value of the latent heat of fusion), it is therefore obvious that the depth to which the freezing temperature can penetrate is less for low dry density.

The negligible effect of dry density on the rate of freezing temperature penetration in the closed system, as indicated by the experimental results, probably illustrates that the effect of the latent heat of fusion on the rate of temperature penetration is relatively less significant than the effect of excess water supply, at least for the conditions investigated. Temperature increase due to the dissipation of the latent heat of fusion of soil moisture for the range of dry densities studied was computed. It was found that the difference in temperature increase between the largest and smallest dry densities (i.e., 108 pcf and 92 pcf) was not more than 1 F. Therefore, the results did not show appreciably the effect of dry density on the rate of freezing temperature penetration in the closed system.

Figure 7 shows the effect of degree of saturation on the rate of freezing temperature penetration. It is seen that, under a constant dry density, the rate of freezing temperature penetration increased as the degree of saturation decreased regardless of the

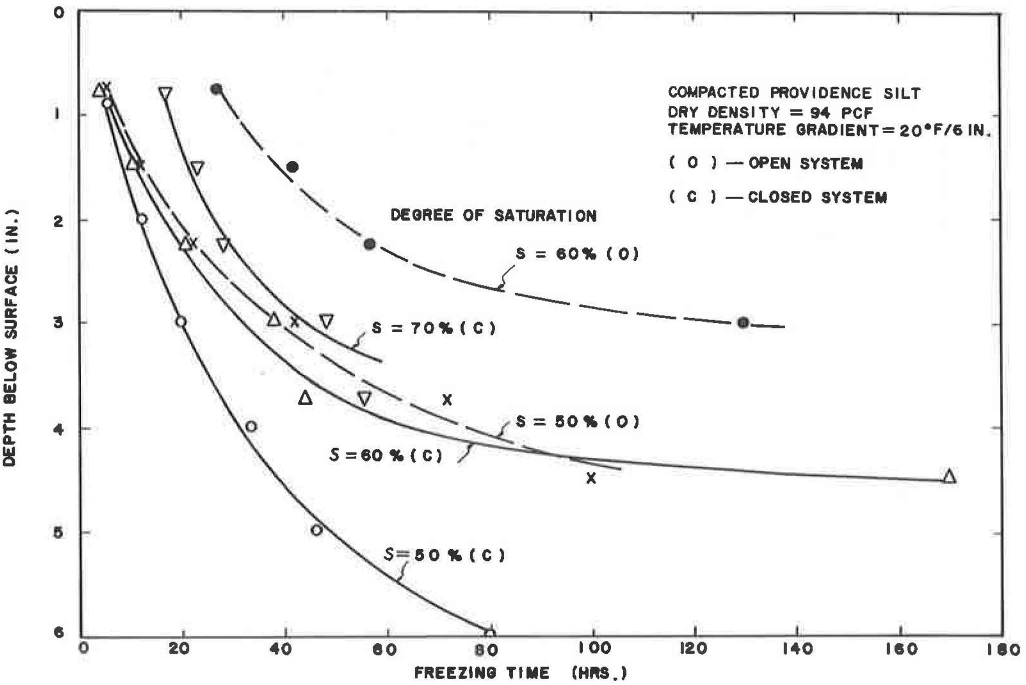

Figure 7. Penetration of 32 F temperature as a function of freezing time for a constant dry density in both open and closed systems.

nature of the testing system. This is as would be expected because a high degree of saturation, under a constant dry density, gives high moisture content that increases not only the amount of latent heat of fusion but also the soil permeability. Both of these factors favor raising soil temperature and impeding freezing temperature penetration. It is also seen that, with all other factors being equal, the depth to which the freezing temperature penetrates within a constant freezing time was greater in the closed system than in the open system.

The effect of soil texture on the rate of freezing temperature penetration is shown in Figures 8 and 9. Figure 8 shows the variation of temperature at midheight of the test specimens with time. It is seen that the rate of temperature variation with time approached zero sooner for the soil sample containing a higher percentage of the fraction smaller than 0.002 mm. Figure 9 shows that, among the 3 soils tested, the greatest depth to which the freezing temperature could penetrate decreased as content of fine fraction increased. In addition, the rate of frost penetration increased as the percentage of fine fraction increased, at least to a depth of 2.25 in. Below a depth of 2.25 in., however, the rate tended to decrease as the content of fines increased.

The percentage of fine fraction in a soil mass is an important consideration because the pore size decreases as this percentage increases. Under a constant degree of saturation and dry density, the consequence of reduction in pore size is to lower the freezing point of the pore water and to decrease the amount of pore water that can move freely without the influence of particle surface forces. As a result, the soil with higher content of fine fraction would be subject to a rapid frost penetration. The reason for the experimental results shown in Figure 9 is not fully understood, but the slower rate of frost penetration at a depth greater than 2.25 in. for the soil containing a higher percentage of fines might be due to retardation resulting from some factors such as excess water supply from the bottom of the test specimens. The results of the final water content measurements shown in Figure 10 could be used to support, at least

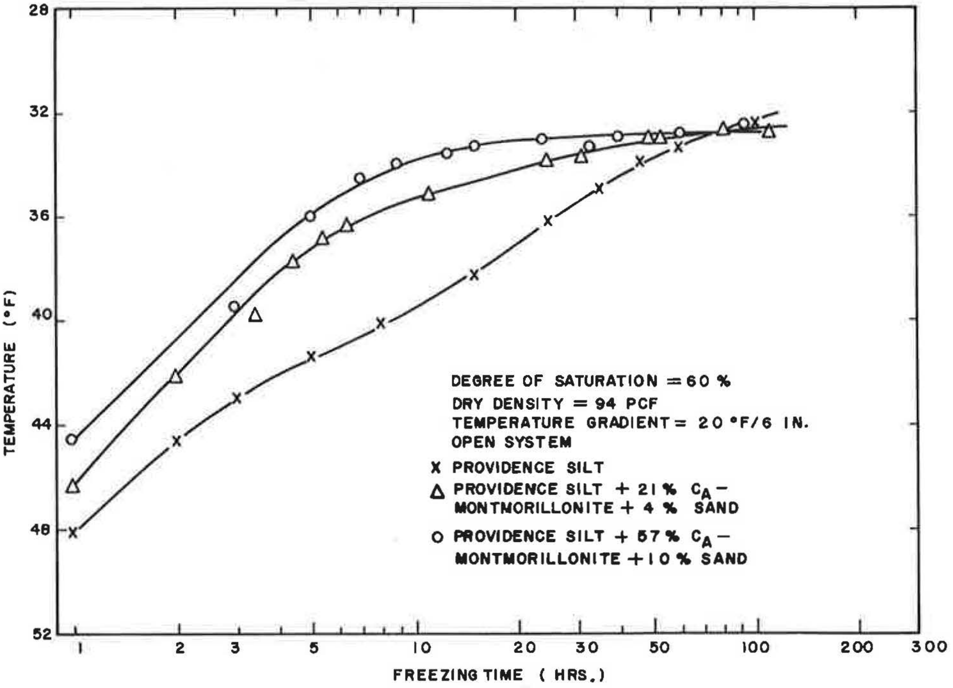

Figure 8. Variation of temperature at midheight of test specimens with time for different soil textures in open system.

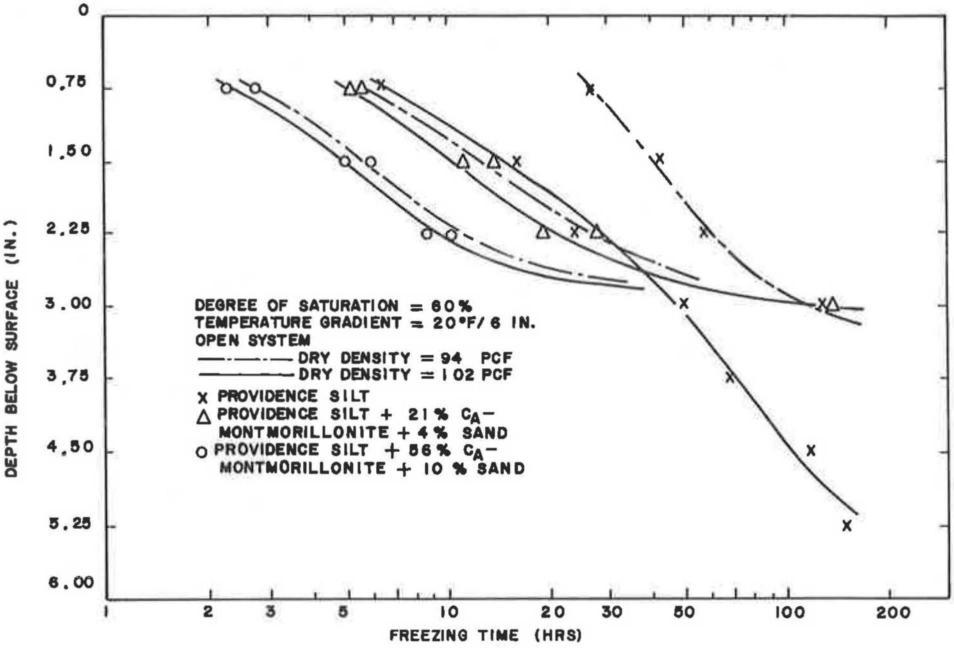

Figure 9. Penetration of 32 F temperature as a function of freezing time for different soil textures in open system.

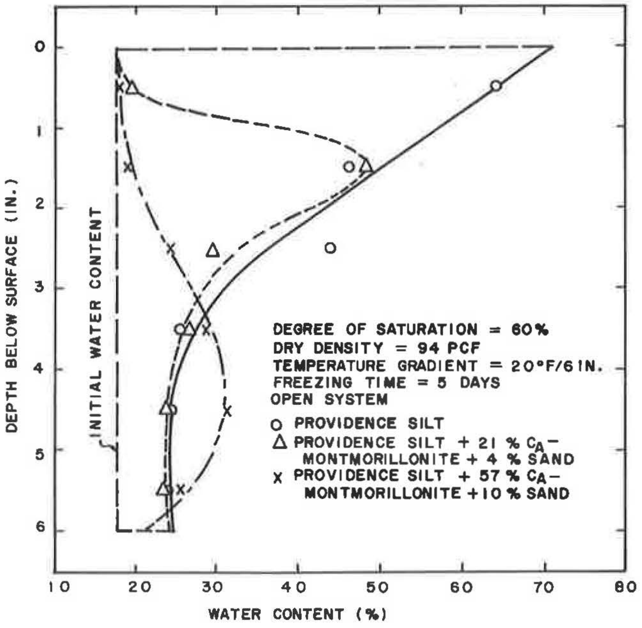

Figure 10. Final water content distribution with depth for different soil textures in open system.

partly, the reason. Figure 10 shows that the distribution of final water contents was such that the maximum height supplied by the excess water decreased as the content of fine particles increased.

Final Water Content

The water content distribution of test specimens, after having been frozen for 5 days, was determined by splitting the specimen into 6 horizontal segments of equal length. In general, the final water content distribution for compacted Providence silt decreased as depth below the surface increased, as shown in Figure 11. Because there was neither moisture evaporation from the top nor water supply from the bottom in the closed system, the average final water content should be equal to the initial water content; that is, the moisture increase in the upper portion should be equal to the moisture decrease in the lower portion of the test specimen. In the open system, because of the excess water supply from the bottom, the average final water content was always larger than the initial water content. In addition, the water content increase in the top 1 in. of the test specimen was considerably larger than the average overall increase.

The water content increase (i.e., the difference between the final and initial water contents) in the top 1 in. of the test specimens varied appreciably with varying molding conditions. Figures 12 and 13 show that the water content increase at the top was greater as molding water content increased but smaller as dry density increased regardless of the nature of the test system. The effect of degree of saturation on the water content increase at the top appeared to be less significant in the closed system than in the open system. The reason might be that, as has been pointed out before, the rate of moisture migration is directly proportional to the permeability of the soil, and the soil permeability is closely related to the degree of saturation. In the closed system, the moisture increase at the top resulted entirely from moisture migrating from the bottom portion. Because most of the moisture transportable under a given external temperature gradient had migrated by the time the test was completed, the effect of degree of saturation on the rate of moisture migration could not be reflected appreciably on the test results. In the open system, the portion of moisture increase due to

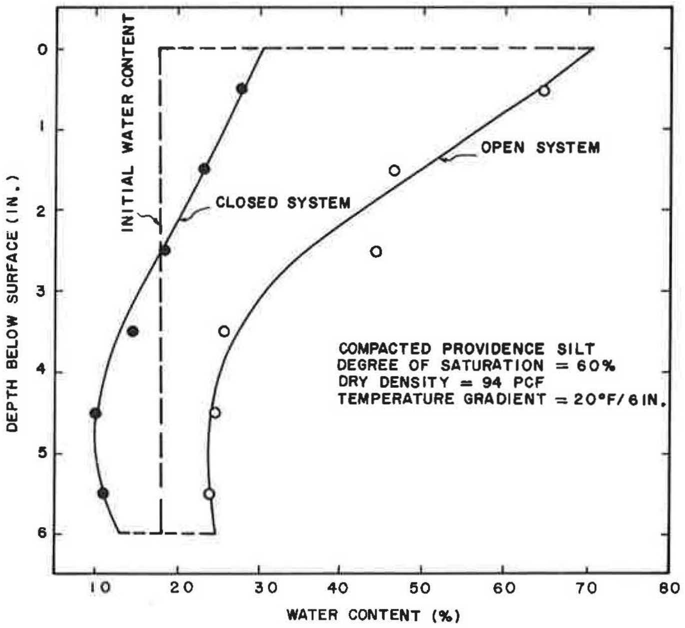

Figure 11. Typical final water content distributions with depth.

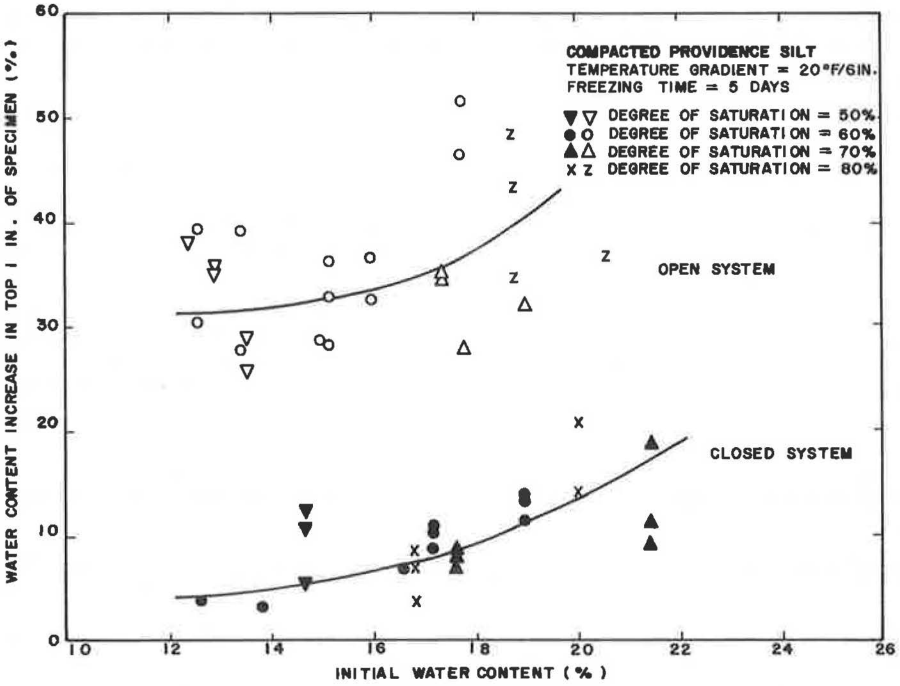

Figure 12. Influence of initial water content on water content increase in top 1 in. of test specimens for Providence silt.

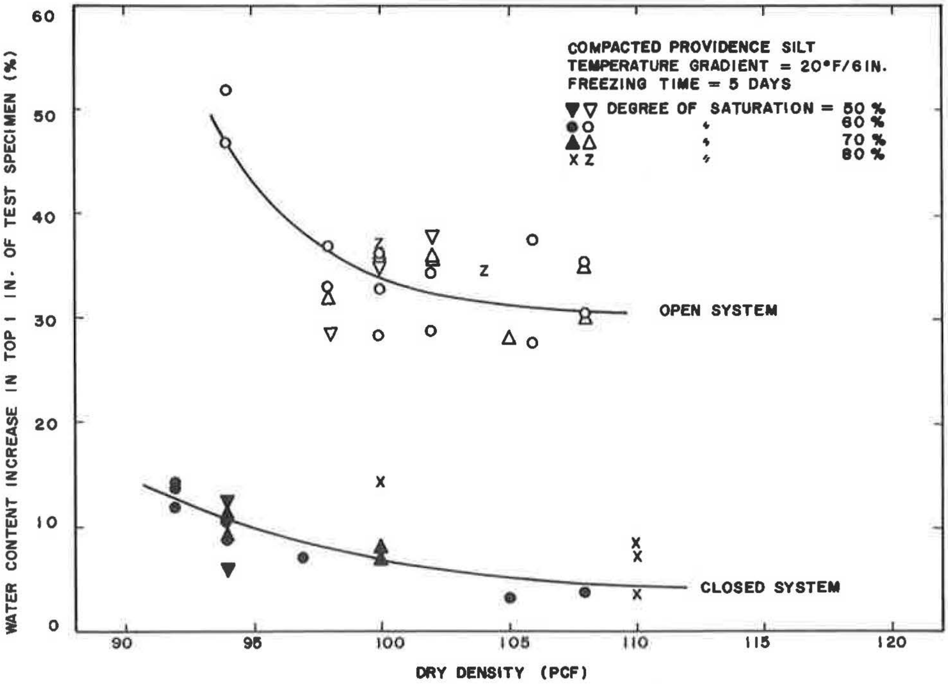

Figure 13. Influence of dry density on water content increase in top 1 in. of test specimens for Providence silt.

excess water supply from the bottom varied with various degrees of saturation and resulted in different amounts of moisture increase at the end of the test. However, no definite trend was obtained to indicate the consequent effect of the degree of saturation.

The general feature of final water content distribution with depth changed significantly with changing soil textures. It was found that the depth at which the maximum final water content occurred increased as the percentage of fine fraction smaller than clay size (0.002 mm) increased. Typical curves of the distribution are shown in Figure 10. The difference may be attributed to the effect of pore size. Because decreasing pore size increases the energy required to cause the same amount of water flow, the height at which the maximum moisture content occurs increases as pore size increases, that is, as fine content decreases. Following the same reasoning, we can conclude that the average overall water content increase would be less as fine-grain content increased.

Frost Heave

Test results show that considerably less heaving developed in the closed system than in the open system. Some specimens in the closed system even showed shrinkage or contraction that resulted from consolidation within the lower portion of the test specimens because of soil moisture that migrated to the upper portion.

Variation of heaving with freezing time was such that the slope of the curves decreased rapidly as duration of freezing increased and eventually approached almost a constant value. The maximum slopes, which were equivalent to the maximum rate of heave, increased as dry density increased, as shown in Figure 14.

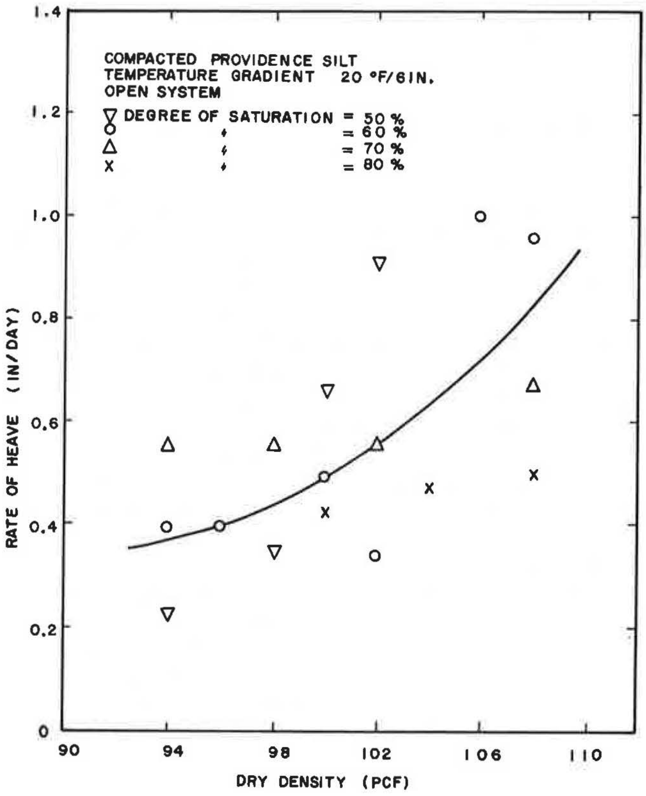

Figure 14. Maximum rate of heave versus dry density for Providence silt.

An increase in the rate of frost heave with an increase in dry density, however, does not necessarily imply that the overall heaving would follow the same trend. Instead, Figure 15 shows that, within the range of conditions investigated, for a given degree of saturation, total heave decreased linearly as dry density increased. The slope of the lines increased as degree of saturation increased. Also, for a given dry density, the higher the degree of saturation is, the higher the heaving rate will be. Figure 15 also shows that total heave increased as molding moisture content increased for a constant dry density, and increased as degree of saturation increased.

The effect of compaction on frost heaving should be a combined effect of molding moisture content, dry density, degree of saturation, and the like. A standard AASHO compaction curve, shown in Figure 15, illustrates that, for the conditions under investigation, frost heave always increased as molding water content increased no matter how the dry density varied. This implies

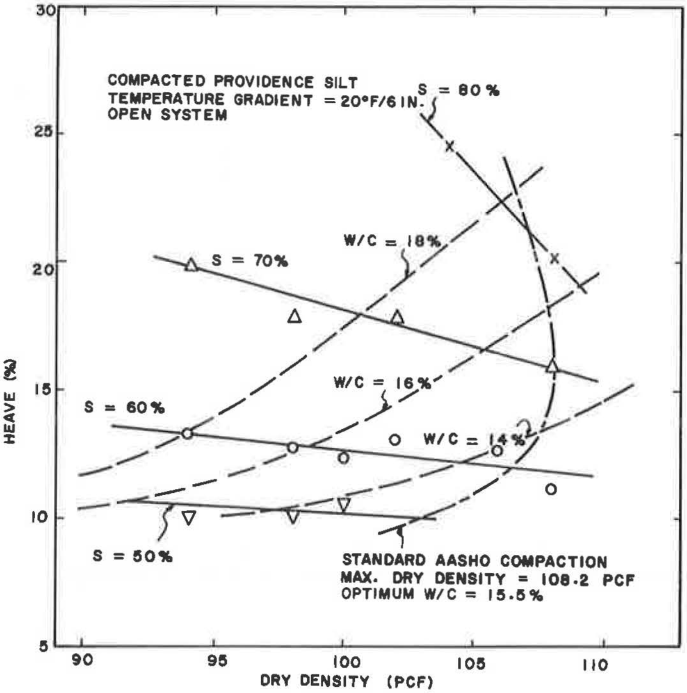

Figure 15. Total heave as a function of dry density.

that the effect of dry density was masked by the combined effect of molding water content and degree of saturation.

Figure 16 shows the difference in the rate of heaving for different soil textures compacted at the same dry density and degree of saturation. It is noted that increasing the fine grain fraction (smaller than 0.002 mm) decreased the rate of heaving. In addition, the intensity of heaving decreased as the percentage of fine fraction increased.

Total heave was plotted versus average water content increase for various degrees of saturation in Providence silt and in various soil textures with 60 percent degree of saturation, as shown in Figure 17. Total heave increased almost linearly with greater average water content increase. The higher the degree of saturation was, for a given water content increase, the higher the heave was. This could be expected because the higher the degree of saturation was, the smaller the pore size for a constant moisture content was, or the larger the volume of pore water was for a constant dry density. The smaller pore size would give greater volume expansion under the same moisture increase, whereas the larger volume of pore water would make the formation of bigger ice lenses possible. Consequently, for a given amount of water content increase, heave increased as the degree of saturation increased.

A marked difference in the slopes of the linear relationships for different soil textures is noted (Fig. 17). The higher the content of fines is (smaller than 0.002 mm), the smaller the slope will be. The test results may emphasize the effect of the size of ice lenses on the overall volume change of the test specimens because, as will be seen later, it was observed from the X-ray radiograph that the thickness of ice layers was different for different contents of fine-grain fraction, which was thicker for the soil having less clay-size content.

Ice Segregation

Development of ice segregation in the test specimens was studied by using an X-ray radiograph and by directly observing ice lenses by splitting the specimens

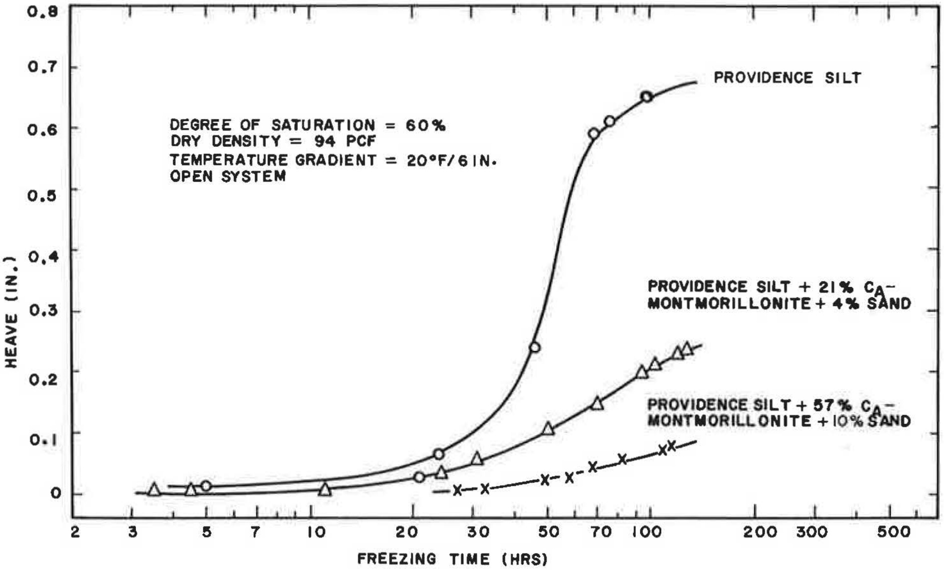

Figure 16. Variation of total heave with freezing time for different soil textures.

longitudinally. The X-ray radiographs were taken immediately before the test and every 24 hours during testing. It was found that, in general, the size of ice lenses was much smaller in the closed system than in the open system and that in the open system ice lenses decreased in size as percentage of fines increased.

Depth to the ice front was measured directly from the radiographs. The depth increased at freezing time increased at a gradually decreasing rate, as shown in Figure 18. Penetration of the ice front approached a maximum sooner in the closed system than in the open system; the maximum penetration by the end of testing was smaller in the closed system than in the open system. In the open system, the depth to the ice front increased as the degree of saturation increased while dry density was constant, and increased as dry density decreased while degree of saturation was constant. Depth to the ice front was smaller for the soil samples containing higher percentages of fines.

SUMMARY AND CONCLUSIONS

The frost behaviors of 3 soils compacted by using various compaction conditions were studied by means of a unidirectional penetration of freezing temperature under a temperature gradient of 20 F/6 in. (25 and 45 F at top and bottom respectively of 6-in. high test specimens). The results of this study have presented a more complete picture of the influence of factors on the frost behavior of compacted soils. It is believed that recognition of the importance of the many factors controlling frost action may aid in the selection of appropriate compaction conditions and in the improvement of methods in engineering practice for predicting the effects of frost action. From the results of this study, the following summary and conclusions appear warranted:

Freezing Temperature Penetration

1. The rate of freezing temperature (32 F) penetration decreased as freezing time increased but was faster in the closed system than in the open system.
2. Under a constant degree of saturation, the rate and the maximum depth of freezing temperature penetration increased as dry density increased in the open system; however, the effect of dry density was insignificant in the closed system.

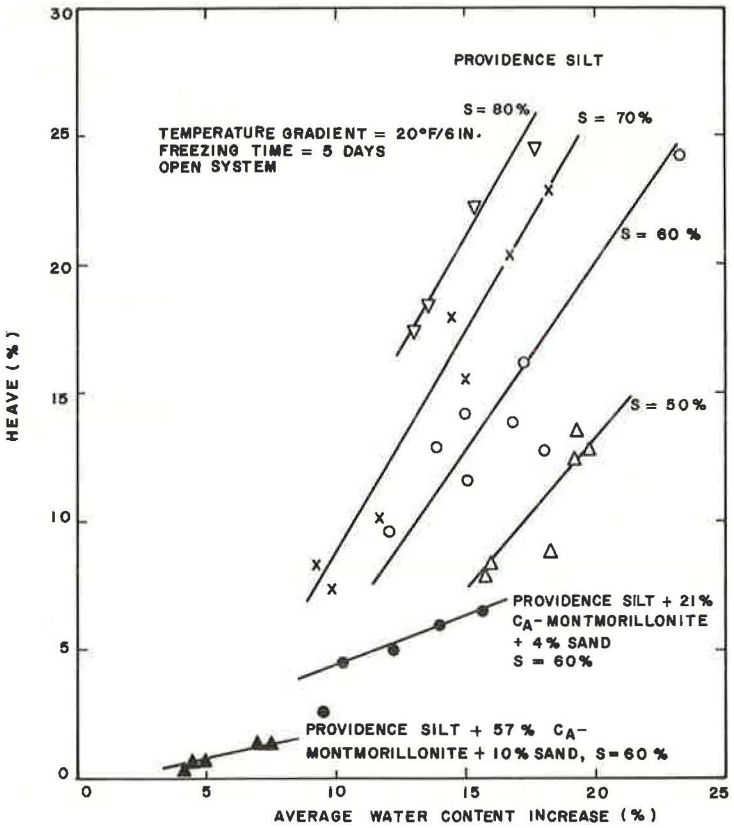

Figure 17. Relationship between total heave and average water content increase.

3. Under a constant dry density, the rate of freezing temperature penetration increased as degree of saturation decreased.

4. For the particular test conditions used, the rate of frost penetration increased above a depth of 2.25 in. as the content of grains smaller than clay size (0.002 mm) increased. Below a depth of 2.25 in., the rate tended to decrease as the content of fines increased.

Final Water Content

5. Although other factors were equal, there was a greater water content increase in the top 1 in. of the test specimens respectively as molding moisture content increased, dry density decreased, or content of fine fraction smaller than clay size decreased.

6. The final water content distribution with depth for various soil textures was such that the depth at which the maximum occurred increased as percentage of fines increased.

Frost Heave

7. Increasing dry density increased the maximum rate of frost heaving but decreased linearly the total heave for a constant degree of saturation. The higher the degree of saturation was, the larger the amount of heave was.

8. Frost heave of soils that were compacted by using a constant compaction effort (e.g., standard AASHO compaction) increased as molding moisture content increased no matter how the dry density changed.

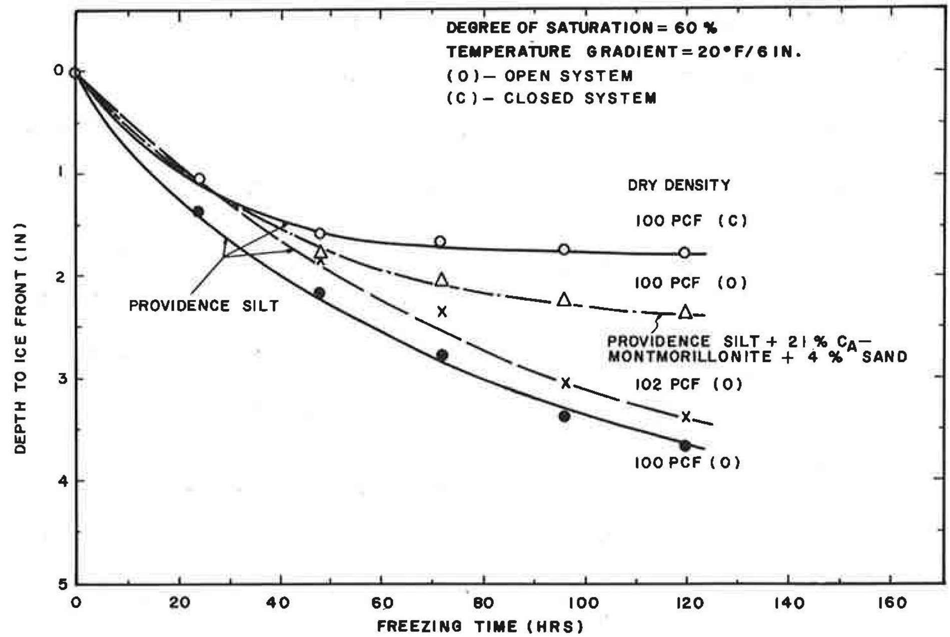

Figure 18. Penetration of ice front with freezing time.

9. Even though the content of sand size was kept constant, frost heave decreased as clay size content increased, i.e., as silt size content decreased.

10. Within the conditions investigated, observations were made of linear relationships between total heave and average water content increase for Providence silt compacted at various degrees of saturation and for different soil textures under a constant degree of saturation.

Ice Segregation

11. Larger ice lenses and greater depth of ice front penetration were given by the open system than by the closed system. Furthermore, in the open system, the size of ice lenses and the thickness of ice layer decreased as percentage of fines increased.

ACKNOWLEDGMENT

The writers are grateful to the following: Water Resources Research Center, U.S. Department of the Interior, for support of this research; David Ding-Jung Pang and Jsung-teh Sung for conducting the testing program; Milton T. Huston, Soil Mechanics Laboratory, University of Rhode Island, for assistance in the development of testing apparatus; and James K. Mitchell, University of California at Berkeley, for reviewing the manuscript. The drawings were prepared by Wen-hsiung Chen.

REFERENCES

1. Taber, S. Frost Heaving. Jour. of Geology, Vol. 37, No. 1, 1929.
2. Taber, S. The Mechanism of Frost Heaving. Jour. of Geology, Vol. 38, 1930.
3. Beskow, G. Soil Freezing and Frost Heaving With Special Application to Roads and Railroads, 1935. Osterberg, J. O., tr., Northwestern Univ., 1947.
4. Martin, R. T. Rhythmic Ice Banding in Soil. HRB Bull. 218, 1959, pp. 11-23.
5. Penner, E. Soil Moisture Movement During Ice Segregation. HRB Bull. 135, 1956, pp. 109-118.

6. Penner, E. Soil Moisture Tension and Ice Segregation. HRB Bull. 168, 1957, pp. 50-64.
7. Penner, E. The Mechanism of Frost Heaving in Soils. HRB Bull. 225, 1959, pp. 1-22.
8. Casagrande, A. Discussion on Frost Heaving. HRB Proc., Vol. 11, Pt. 1, 1932, pp. 168-172.
9. Penner, E. The Importance of Freezing Rate in Frost Action in Soils. Proc. ASTM, Vol. 60, 1960.
10. Haley, J. F., and Kaplar, C. W. Cold-Room Studies of Frost Action in Soils. HRB Spec. Rept. 2, 1952, pp. 246-267.
11. Haley, J. F. Cold-Room Studies of Frost Action in Soils, A Progress Report. HRB Bull. 71, 1953, pp. 1-18.
12. Linell, K. A., and Kaplar, C. W. The Factor of Soil and Material Type in Frost Action. HRB Bull. 225, 1959, pp. 81-128.
13. Frost Action in Soils, A Symposium. HRB Spec. Rept. 2, 1952, 385 pp.
14. Lambe, T. W. Modification of Frost-Heaving of Soils With Additives. HRB Bull. 135, 1956, pp. 1-23.
15. Tsytovich, N. A. Bases and Foundations on Frozen Soils. HRB Spec. Rept. 58, 1960, 93 pp.
16. Winn, H. F. Frost Action in Stabilized Soil Mixtures. HRB Proc., Vol. 18, Pt. 1, 1938, pp. 264-290.
17. Richards, L. A., and Wadleigh, C. H. Soil Physical Conditions and Plant Growth. Academic Press, N.Y., 1952, Chap. 3.

APPENDIX

DESCRIPTION OF TEST APPARATUS

Cold Chest

A refrigerator having an inside dimension approximately 23 in. wide by 13.5 in. long by 31 in. high was used to control temperature within the test chamber. The size of the test chamber was large enough to accommodate 5 test specimens. The test specimens, contained in Lucite cylinders, were separated with granular insulation, a commercial mica, so that freezing temperature could only penetrate unidirectionally from the top of the test specimens. Plates of Styrofoam were place against the door of the cold chest to retain the commercial mica and also to prevent both freezing temperature and outside temperature from penetrating laterally into the bottom of the test chamber.

The temperature at the bottom of the test chamber was kept uniform and constant at 45 F by means of water circulated by a pump. The level of the circulating water was so controlled by an overflow cup set outside of the refrigerator that it was just in touch with the bottom of the test samples. Besides controlling the temperature, the circulating water also served as a constant groundwater table as in the field condition. This simulated groundwater table could be used to supply additional water during freezing when a porous stone was set underneath the soil samples. The testing system in this case is called the open system. Whenever the closed system was desired (i.e., no excess water supply), the porous stone was replaced by a thin metal plate.

Temperature-Measuring System

The temperature-measuring system was composed of copper-constantan thermocouples and a readout unit for measuring soil temperature as well as the air and water temperatures in the test chamber. The readout unit was a reflecting type of galvanometer, manufactured by the Leeds and Northrup Company, No. 2436-b. The measuring instrument had a sensitivity of 0.1 microamperes per scale division and a system resistance of 35 ohms. The complete assembly was set beside the refrigerator so that readings could be taken without disturbing the test chamber temperature.

Among 5 test soil specimens, only the one at the center of the group was used to measure soil temperature. The thermocouples were connected to the test soil specimen at intervals of 0.75 in. through the height of the specimen so that the rate of temperature penetration could be measured directly (Fig. 1). The holes on the Lucite cylinder for the thermocouples were staggered about the circumference of the cylinder.

Volume Change Measuring System

Dial gages reading to 0.001 in. were used to measure uniaxial heaving or shrinking of the test samples. The dial gages were fastened on horizontal rods that, in turn, were fixed on the wall of the test chamber. A thin metal plate was set between the dial gage and the test specimen to ensure a smooth surface and also to prevent the evaporation of soil moisture. A light, controlled by a switch located outside the refrigerator, was used to light the test chamber so that gage readings could be taken more easily. All readings could be taken through the transparent door of the refrigerator without disturbing the testing process.

X-Ray Machine

The X-ray machine was a modified medical X-ray unit manufactured by the Picker X-Ray Corporation. It was operated with a voltage of 80 kilovolts and a current of 15 milliamperes. For observation of the development of ice segregation, X-ray radiographs were taken every 24 hours for the sample located at the front left side of the group.