The Frost Behavior of Soils. I. Vertical Sorting

ARTURO E. CORTE, Contract Scientist, U.S. Army Snow Ice and Permafrost Research Establishment, Wilmette, Ill.

Studies in permafrost areas show that a particle-size sorting occurs in saturated granular soils due to freeze-thaw cycling. This phenomenon is evidenced by a gradual change in size of soil grains, with the fines at the bottom of the active layer and the coarse at the surface. This happens in well-graded materials with and without particles finer than 0.02 mm.

In laboratory experiments soil samples were subjected to alternate freezing-and-thawing cycles with the test specimens completely saturated. Series have been run in which freezing and thawing both progressed from the top down, and others in which freezing occurred from the bottom and thawing from the top. The soil materials used were well-graded sandy gravels lacking the 0.02-mm fraction.

The tests show that all samples developed vertical sorting and changes in density (thawed condition) as the freezing-and-thawing cycles proceed, and that the density change is a function of the initial density and the speed of freezing.

With a freezing rate of 0.6 mm per hr, a sample that has 14 percent finer than 0.074 mm developed sorting and increased 10 percent in volume after 5 cycles of freeze-thaw. The rate of movement of the 0.074-mm fraction is 0.25 percent per cycle. A sample that has 0 percent finer than 0.074 mm also produced sorting and increased up to 6 percent in volume after 10 cycles. These tests were performed without surcharge on the samples. It is possible that this decrease in density might be a result of the migration of smaller particles from the voids between larger ones.

It is therefore apparent that a mixed soil subjected to freeze-thaw cycles becomes vertically sorted until a filter system is established: that is, the material in one layer cannot pass through an intervening layer into a third. In practice, this principle implies (a) that a well-graded gravelly soil, with or without fines, will be sorted and a density change will take place when it is subjected to a sufficient number of freeze-thaw cycles; and (b) that, although a soil may not foster formation of ground ice during the first freeze cycle, the chance for such a formation will increase during subsequent cycles, as more of the finer material is concentrated at the bottom of the freeze-thaw layer.

More tests are being conducted to determine (a) the segregation effects when the zero line moves vertically, instead of horizontally, into the soil; (b) the effect of sphericity of the particles; and (c) composition of the finer fraction.

● FARMERS in areas of intense winter freeze have reported the appearance of stones at the ground surface and the heaving of fence posts. These stones and posts are supposed to have been pushed out of the soil by repeated freezing and thawing action. Högbom (1), Hamberg (2), Hesselman (3), and Beskow (4) explain this phenomenon as a result of expansion during freezing. During thawing, the stones do not settle to the same place because of the reorganization of the soil particles. Högbom and Hamberg considered

Figure 1. After 6 freeze-thaw cycles heaving occurring in the outer and middle circles of marbles.

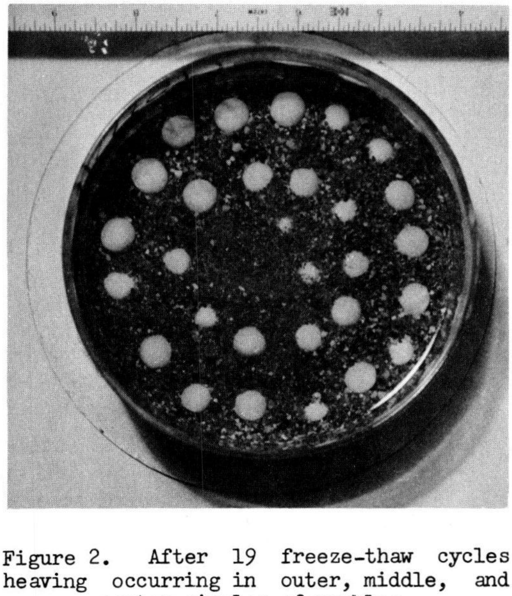


Figure 2. After 19 freeze-thaw cycles heaving occurring in outer, middle, and center circles of marbles.

that formation of ice at the bottom of the stones is a necessary condition for the heaving.

The literature on formation of patterns produced by freezing and thawing is voluminous and the problem of sorting is treated in more than 20 theories (5, p. 568-69). In spite of so many theories, there are no basic field and laboratory experiments on this problem of sorting.

Vilborg (6) has demonstrated that the soil particles surrounding stones are finer than particles located under them. The presence of coarse material under the stones is attributed to mechanical sorting in the cavity beneath the stone when it is lifted during freezing. Concentration of fine particles at the bottom and coarse particles on top of the active layer was reported by Taylor (7) and Corte (8) for the Thule area in northwest Greenland.

With the construction of roads and railways, the effect of frost behavior on soils became a main problem, and during the second and third decade of this century research on frost action was conducted in the U.S. by Taber (9, 10, 11, 12, 13), in Sweden by Beskow (4), in Germany by Casagrande (14) and Dücker (15, 16, 17, 18), in Russia mainly by Tsytovich, N.A. (1957) and others at the Institute of Permafrost V.A. Obruchev.

The effect of grains finer than 0.02 mm, colloids, the mineralogical compositions of the binding material, rate of freezing, effects of loads, etc., have been investigated. To date, it appears that the basic work of Taber and Beskow on ice lenses in fine soils is generally accepted, but there is still much disagreement on the exact mechanism of water movement to feed the growing ice lens and source of energy for heaving. In the last decade, much effort has been expended in studying the problem of frost action.

The thermal properties have been investigated mainly by Kersten (20, 21). The mechanics of frost heaving have been investigated by Penner (22), Jumikis (23), Martin (24), Higashi (25), Cass and Miller (26), and others. The factor of moisture in frost action was reviewed recently by Low and Lovel (27), and it is shown to be an area in which more understanding is required.

According to investigations made at ACFEL, U.S. Army, Corps of Engineers, Linell and Kaplar (28), the control of soil characteristics is the most feasible factor to consider for frost action. The present-day Casagrande criterion of the percentage of the 0.02 mm fraction is a rough rule of thumb, but is the best presently available (28, p. 123). According to practical experience, it is clear today that the knowledge of the

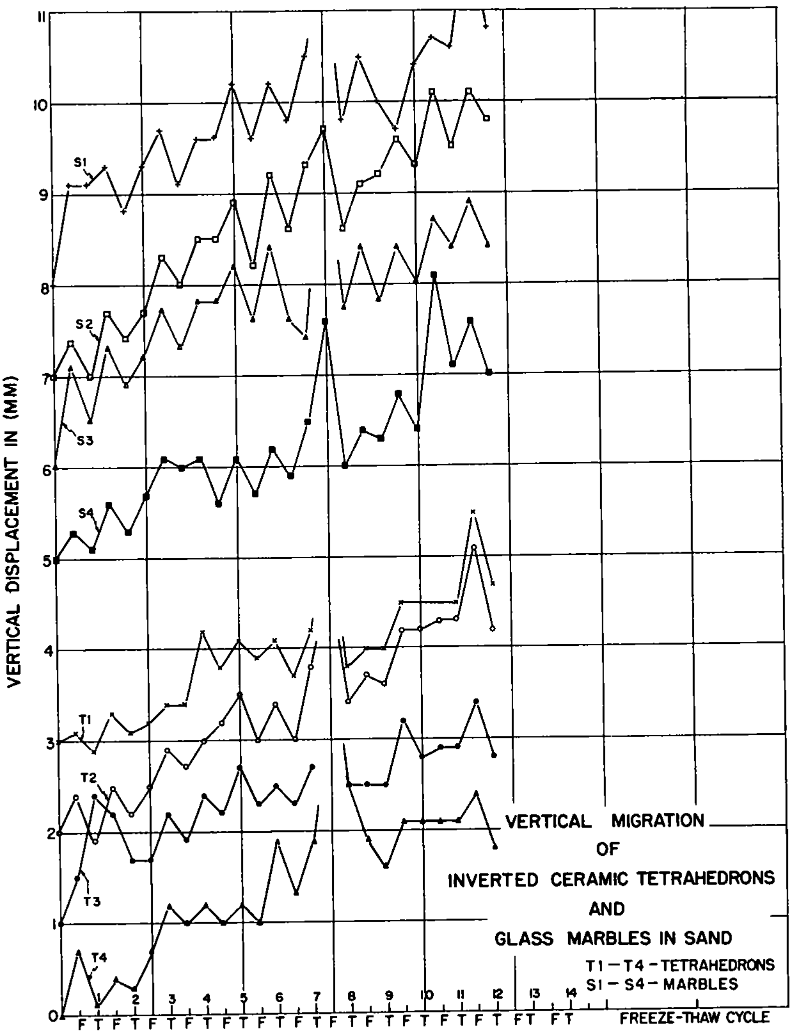


Figure 3.

pedological and geological conditions will increase the understanding of the frost action phenomena (29). According to Tsytovich (19, p. 118), Shusherina* reported in 1955 on the alteration of structural bonds that takes place both on thawing and by cyclic freeze-thaw action in all soils.

The present report considers whether particles move in the soil under freeze-thaw cyclic effect. If particles move, then it will be necessary to analyze under what conditions this happens. Of the many variables involved in freezing and thawing cycles only a few of them will be explored: (a) grain size, (b) speed and direction of freezing, (c) mineralogical composition of the finer fraction, (d) speed of heaving of certain particles shapes, and (e) the effect of freeze-thaw cycles on the breakage of the soil particles. If laboratory experiments simulating natural conditions can demonstrate that particles move, it will be necessary to see if nature develops such segregation and the conditions under which this occurs.

*Shusherina's report is in abstract form and was not available during this report preparation.

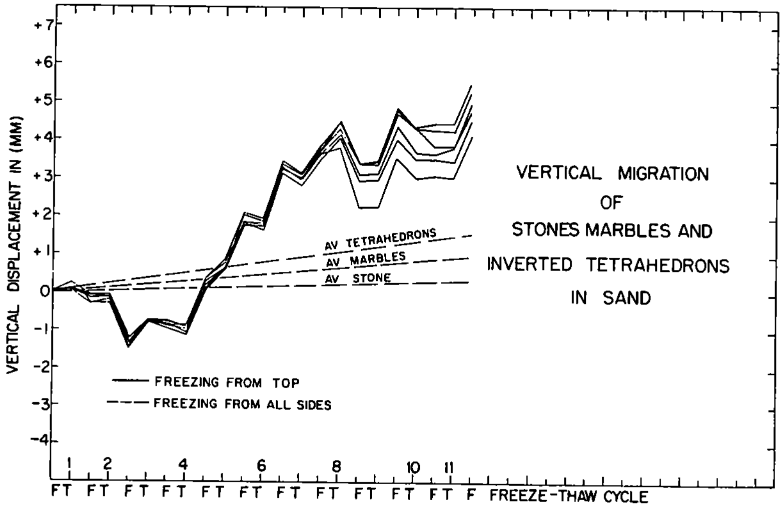


Figure 4.

LABORATORY DATA

Preliminary Experiments

A preliminary experiment was carried on in a glass culture dish in which three circular rows of marbles 1 cm in diameter were covered by a layer of clean, washed sand about 2 cm thick with no particles finer than No. 200 mesh. The sand was washed until all suspended particles were removed by the running water. In the dish, water was kept about 4 cm above the sand surface. The culture dish was brought into the -20 C cold room for freezing and was taken into the laboratory at +20 C for thawing. The 4 cm layer of water above the sand surface permitted the sample to freeze and thaw mainly from the bottom upwards, but also from the sides. Before cycling started, the culture dish showed only a sand surface layer. After 6 cycles the outer row of marbles appeared and also some of the inner ones (Fig. 1); after 19 cycles, all the marbles from the two outer rows came up and also two of the central circle (Fig. 2). The sand layer showed a very clear sorting of coarse sand to the top and the fines to the bottom. It is proposed that this rearrangement of particles be called vertical sorting. This experiment demonstrated that clean sand without fines can be sorted by repeated freeze-thaw action and that the coarsest particles are extruded out of the sand. The implications of such movements were clear, and additional experiments were carried on in open containers in order to see the behavior of different geometric bodies. Again clean sand was used in noninsulated containers. Two geometric shapes were used: glass spheres 2.6 cm in diameter and ceramic tetrahedrons 2 cm high. Four tetrahedrons were placed inverted into the sand with only a small part of the base near the sand surface so that its position could be observed. Four marbles were also placed into the sand so that the upper part of each was visible. The positions of the particles were measured with Vernier calipers after every freezing-and-thawing cycle. During the freezing cycle there was no problem in measuring the particle, but at thaw stage there was some slight pushing down of the particle with the Vernier gage. Therefore, the actual position of the particle was slightly higher than shown in the curve in Figure 3. It was found that the glass marbles moved upward faster than the ceramic tetrahedrons, the average rate of heave being 0.22 mm per cycle for the marbles and 0.18 mm per cycle for the tetrahedrons. The rate of movement of the ceramic tetrahedrons was less than when they were not inverted: 0.09 mm per cycle.

Because these experiments were carried out in containers without insulation, freezing and thawing proceeded from all direction. To find out if particles would move when

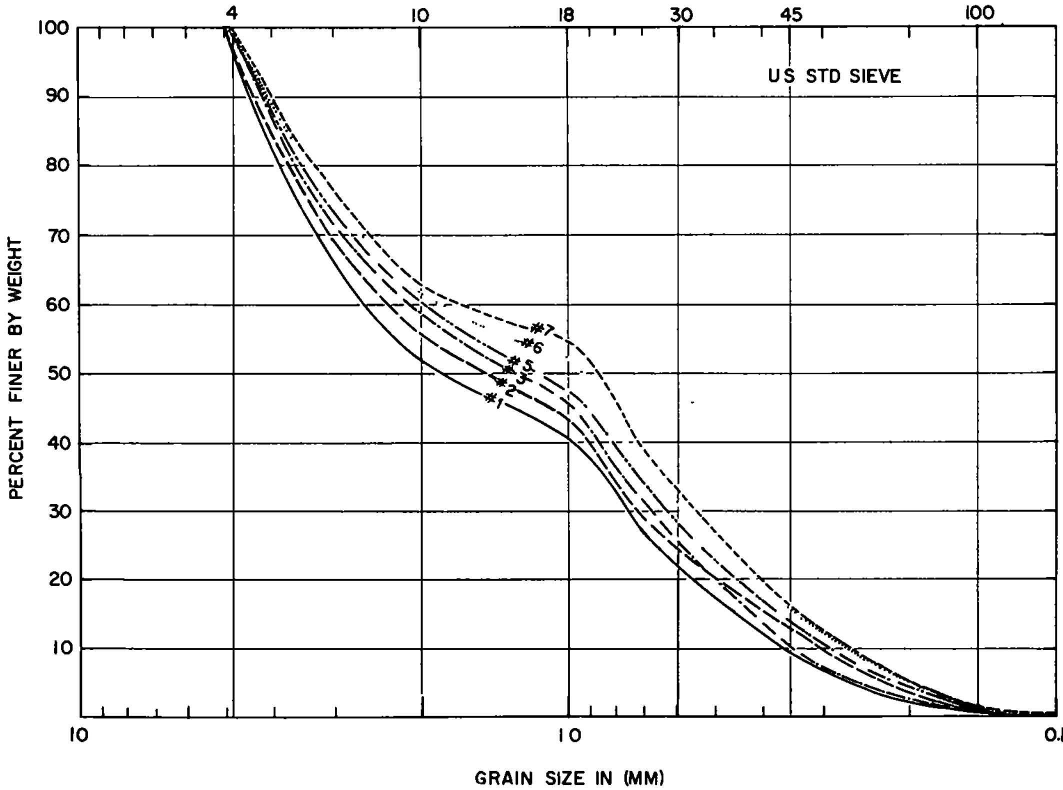


Figure 5. Vertical sorting produced in sample of commercial sand after 20 cycles of freeze-thaw, freezing from the top at a 1.4 mm per hr. Total thickness of layer: 21.5 cm: thickness of each analyzed layer: 3.0 cm.

freezing occurred from the top, an insulated cabinet designed by Schmertman (30) was used. This cabinet provided good temperature control, but could handle only one sample in each cabinet. A clean sample of commercial sand was placed in the container without compaction and two marbles, 2.6 cm in diameter, two tetrahedrons 2 cm high, and two stones about 2 cm in diameter were buried in the sand at a depth of 12 cm. A thin piano wire was glued to each particle so that each position could be read by measuring the top of the steel wire. The sample was then subjected to 20 cycles of freeze-thaw with the freezing rate of the order of 1.4 mm per hr, and the thawing rate twice that value. The water level was kept at the top of the sample by pouring water in from the top of the cylinder.

A similar sample including marbles, tetrahedrons, and stones, was placed in an open plastic pan and placed in the cold room along with the insulated container. As expected, the sample in the plastic pan froze at a rate that was 2 to 3 times faster (approximately 2.8 to 4.2 mm per hr) than the insulated sample.

In spite of the various incompatibilities of the two tests and the inherent limitation of the equipment used in this preliminary experiment, certain useful observations were made. In both tests the buried marbles, stones, and tetrahedrons were observed to move upward, the magnitudes being greater in the case of the unidirectional freezing than in the case of freezing from all sides. Figure 4 is a plot of these motions. The linearity of the broken lines resulted from measuring only at the thawed condition after every fifth cycle, whereas in the unidirectional freezing test measurements were taken at the thawed and frozen stage of each cycle. A downward displacement of the buried objects was observed during the first two cycles of unidirectional freezing; this was caused by densification of the originally loose sample. Subsequently, the particles were

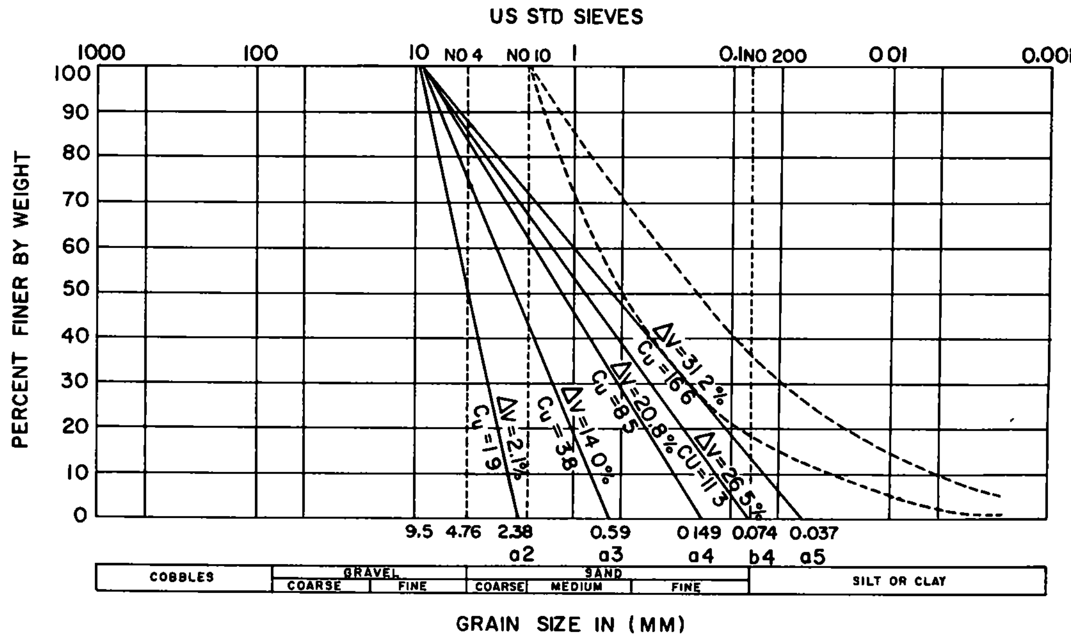


Figure 6. Volume changes, produced by sorting without freezing and thawing, straight graded samples a2, a3, a4, b4, a5 (solid lines) compared with boundary lines of frost susceptible and non-frost susceptible soils (dashed line).

heaved about 6 mm in 9 cycles. Also, at this point in the test the sample height had increased 16 mm. Although the broken lines imply that the heave rate is dependent on particle shape, this conclusion cannot be made from this data, for in other tests, different relative heave rates were obtained for the same particles. After 20 cycles of freezing and thawing, the sample from the insulated cabinet was cut into 7 horizontal layers, each 3 cm thick, and the grain size distribution of each was determined. Curves for the 7 layers (Fig. 5) indicate that a distinctive vertical sorting did occur. The results of this experiment indicate the following:

1. Particle motion depends on the direction of freezing, is probably a function of the rate of freezing, may be a function of the particle shape.
2. Freezing and thawing produces a definite sorting of soil particles by size, the larger moving up and the smaller moving down.

Later it will be shown that the slower the rate of freezing, the greater the volume change. This strongly implies that both heaving and vertical sorting are dependent on the rate of freezing.

Vertical Sorting and Volume Changes Produced by Cyclic Freeze-Thaw

In preceding experiments it was demonstrated that the coarser particles of a mixture migrate upward. It is necessary to find out what happens to the finer fraction. The movement of the coarse fraction could be measured with a gage but the movements of the fines have to be determined by grain size analysis after a certain number of cycles.

For this experiment, five samples were prepared from a commercial sandy gravel; samples were designated: a2, a3, a4, a5. Each grain size falls in a straight line. All samples have a common origin at the No. 10 sieve, and the end of each grain-size line is located at equally spaced intervals differing approximately by a multiple of 4 (Fig. 6). In this manner the uniformity coefficient, $\left(\frac{D_{60}}{D_{10}}\right)$ increases in each sample by

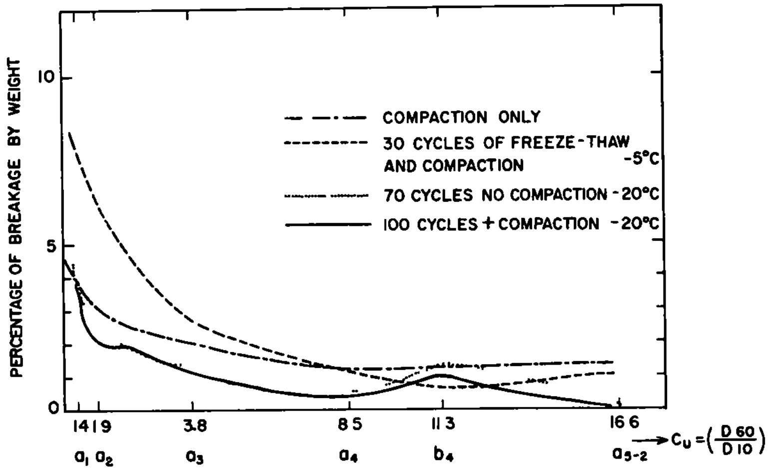


Figure 7. Percentage of breakage as a function of uniformity coefficient.

a multiple of approximately 2. With sample a5, two subsamples were prepared, designated a5-1 and a5-2. For a5-1 the 14 percent finer than the No. 200 sieve is a cohesive fraction taken from a sample of Bloomington till; in a5-2 the same fraction is made of quartz powder, a commercial material, noncohesive, with the trade name of "silicrete." Samples a5-1 and a5-2 are the same grain size but the mineralogical composition of the fines is different. In this way it will be possible to see the effect of the mineralogical composition of the fines on the freeze-thaw section.

Figure 6 also shows that the finest sample, a5, is a line tangent to the lower boundary of the so-called "frost susceptible soils" (4, 14, 31). These samples can be classified according to the United Soil Classification System of the Corps of Engineers (32) as follows:

a2: GP
a3: GP-SP
a4: SP
a5-1: SC
a5-2: SM non-plastic fines, "silicrete"

TABLE 1

Sample	Dry Density (g/cm³)	Dry Density (pcf)
a2	1.529	95.4
a3	1.658	103.5
a4	1.842	114.9
a5-1	1.822	113.7
a5-2	1.842	114.9

Samples were compacted according to Table 1. Samples weighing 2 kg each were placed in layers about 2 cm thick and compacted with several blows of a piston weighing 8 kg. The sample container is a brass cylinder 12.5 cm in diameter and 15 cm high; the bottom of the cylinder had 2.3-mm holes in the bottom for water to enter into the sample.

In the compacting process, special care was taken in order not to produce sorting by compaction. It was observed that when samples were moist no sorting was produced by compaction. The amount of breakage produced under different numbers of freeze-thaw cycles was also determined. The test shows clearly that there is a definite breakage by freeze-thaw cycles. The amount of breakage decreases as the uniformity coefficient of the sample is raised (Fig. 7). It was also observed that there is more breakage at a slow rate of freezing and thawing. There was more breakage after 30 cycles and compaction at -5 C than after 100 cycles and compaction at -20 C. Sample a5-1 with 14 percent passing sieve No. 200 did not show breakage. However, these two last statements need further experimental verification. In the tests it was not intended to correlate amount of breakage and the kind of rock that composes the sample.

Figure 8. Container holding 6 samples, 2 in brass and 4 in lucite cylinders.

The brass cylinders with the compacted samples were placed in a larger container and a mixture of gravelly sand was put around them (Fig. 8). Water entered the container through a pipe connected to a water tank having an adjustable level. The water level was kept constantly at the top of the specimens. An electrically controlled valve between the container with the specimens and the water tank was turned off during freezing and on during thawing. The purpose of this was to create a confined condition such as occurs in the active layer in nature. If there were no valve during freezing, the expansion produced would push the water below the freezing line and cause the water level to rise. It was observed during every cycle that if the valve was open the water rose during every freezing cycle and dropped during thaw. When the active layer freezes there is no place where the water confined between the frozen active layer and the permafrost can go; that is, it is a closed system. For this reason a laboratory closed system simulates the active layer better than an open system. The temperature of the freezing cabinet was measured by thermocouples placed vertically every 2 cm. The temperature distribution in the samples was measured and a flat freezing line was obtained in the specimen. The temperature was controlled chiefly by means of heating tape placed at the bottom of the container, and the freezing rate was determined by the drop of voltage on that heating tape. A drop of 4 volts a day was enough to produce a freezing line penetration of 0.6 mm per hr. The thawing speed was about 6 mm per hr, and it could be produced from the top by infrared lamps placed on top of the freezing cabinet and from the bottom of the specimen by increasing the voltage in heating tape. For this test, thawing was produced only from the top.

Samples a2, a3, a4, a5-1 and a5-2 were subjected to 22 cycles of freeze-thaw. During the cycling process it was observed that the samples increased in volume, and that the volume increase was larger for samples with a higher uniformity coefficient. After 22 cycles the samples were taken out of the cabinet and grain-size analysis was performed in order to determine if vertical sorting had developed. Samples a2, a3, and a4 were cut into 3 layers; each layer was 2.5 cm thick. Samples a5-1 and a5-2 were cut into 5 layers, each 1.6 cm thick. The grain-size analysis shows that all samples developed vertical sorting with the bottom layer finer than the top one (Figs. 9 and 10). The vertical sorting is more striking where the analyzed layer was 1.6 cm thick. The fraction finer than 200 mesh (Fig. 9) decreased from 14 to 10 percent in the upper layer of a5-2 and increased from 14 to 21 percent in

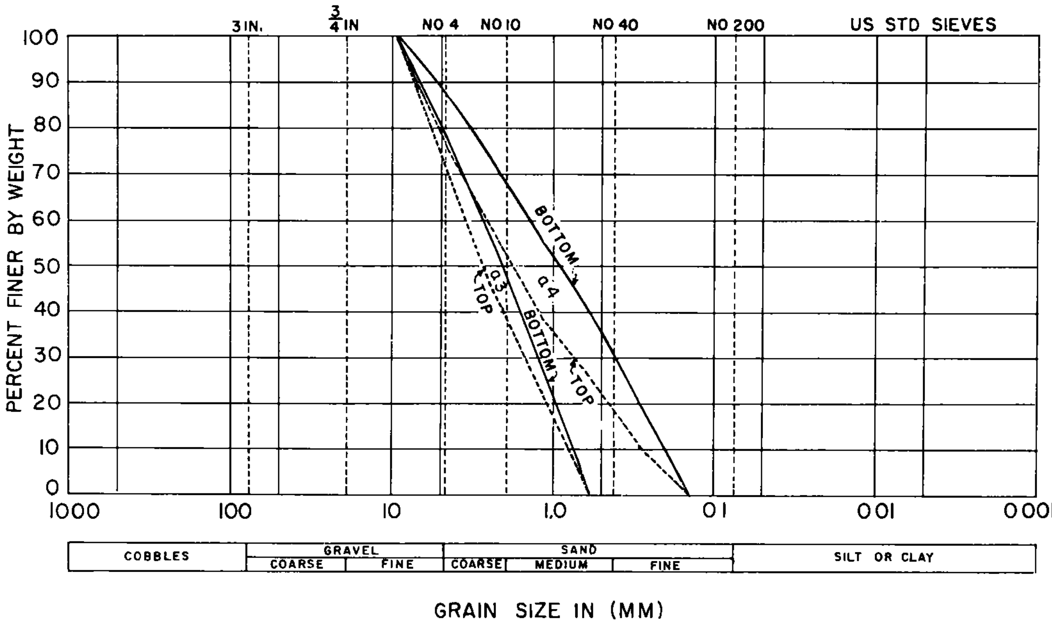


Figure 9. Vertical sorting developed in samples a2 and a5-2 silicrete after 22 cycles of freeze-thaw.

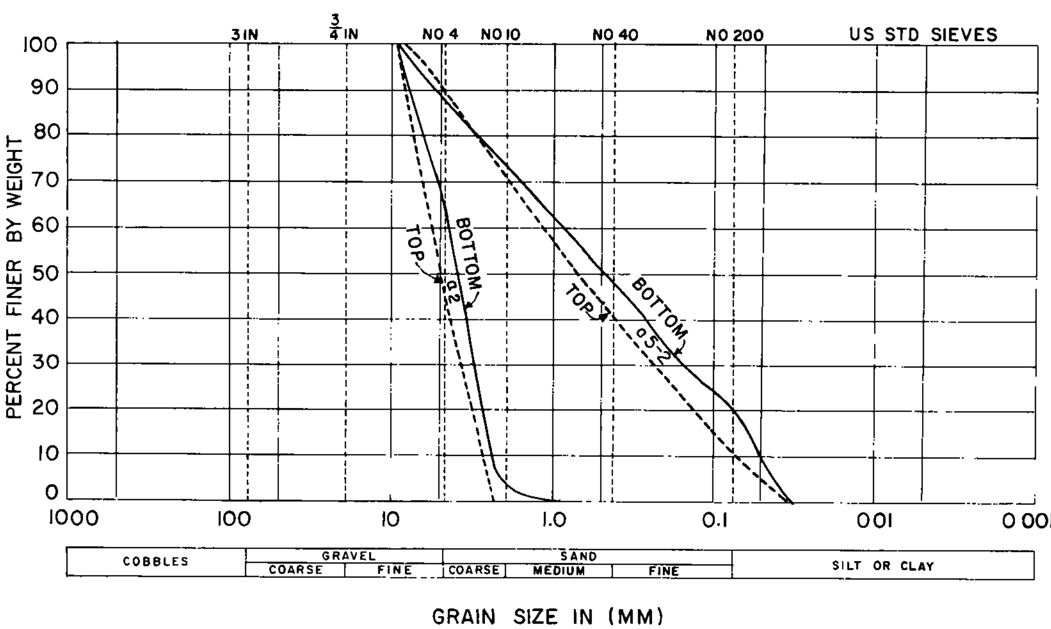


Figure 10. Vertical sorting developed in samples a3 and a4 after 22 cycles of freeze-thaw cycles.

the bottom layer. This indicates that this fraction moved down at a rate of 0.2 percent per cycle and concentrated at the bottom at a rate of 0.3 percent per cycle. This was accomplished at a rate of freezing of 0.6 mm per cycle. In sample a5-1, Bloom-

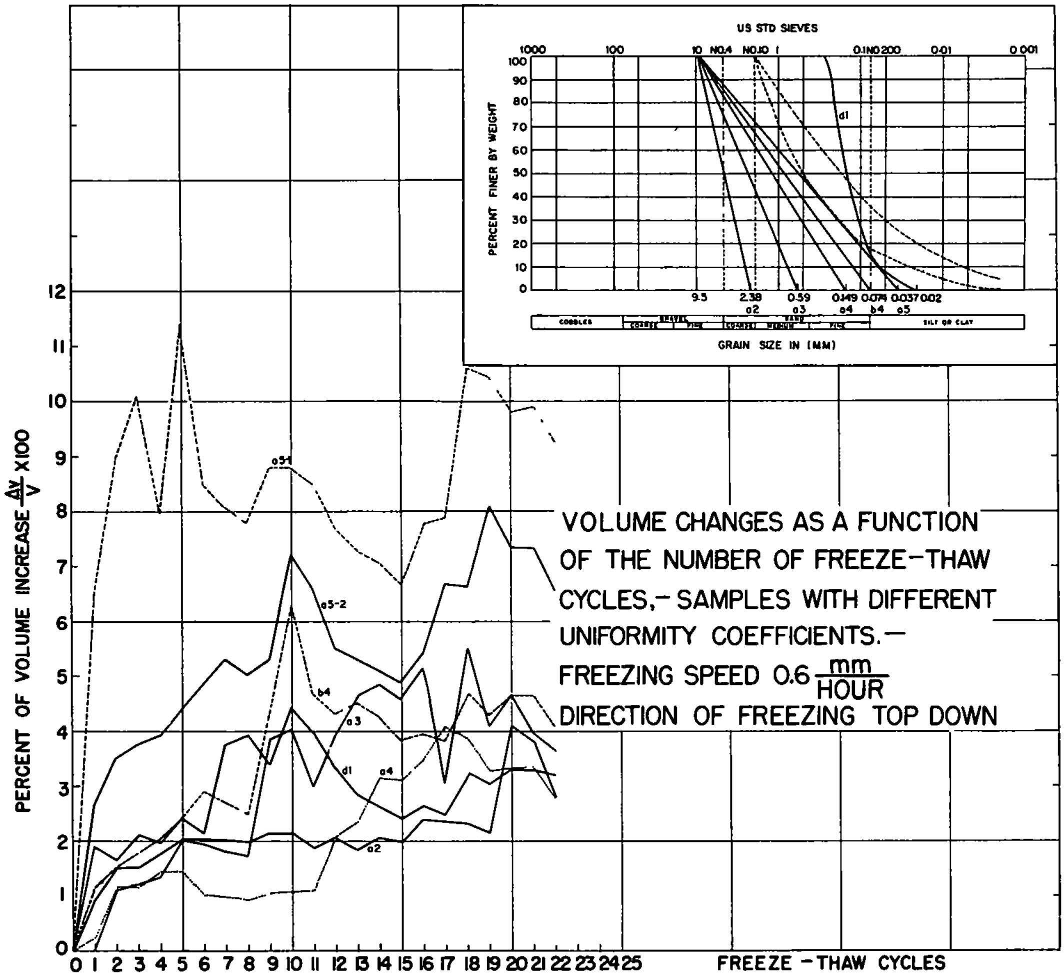


Figure 11.

ington till, the fine fraction moved down only by 1 percent or 0.02 percent per cycle. This is to be attributed to the cohesive properties of the fines which adhere better to the larger particles than the noncohesive fines made of quartz powder.

Hydrometer analysis performed on the fraction passing sieve No. 200 showed that the bottom layer is richer in colloids than the top layer.

This experiment shows the following:

1. Compaction and freeze-thaw cycles produce breakage of the soil grains. The amount of breakage decreases as the uniformity coefficient of the sample is raised.
2. Cyclic freeze-thaw produces vertical sorting with the bottom layer finer than the top one. This vertical sorting is observed in the so-called "non-frost susceptible" soils. Noncohesive soils segregate faster than cohesive materials.

In order to determine the volume change produced by the sorting process, a new test was run in the same freezing cabinet. A Starrett dial gage was inserted in the wall of the brass cylinder. The dial gage could read 0.01-mm vertical displacements.

Samples were compacted by a metal piston, each layer was compacted with 16 blows before placing the next one. The same type of samples was prepared as before: a2, a3, a4, a5-1, and a5-2; with another sample, b4, included having a uniformity coefficient of 26.5 and containing no particles finer than mesh 200 (Fig. 6). All samples are "non-

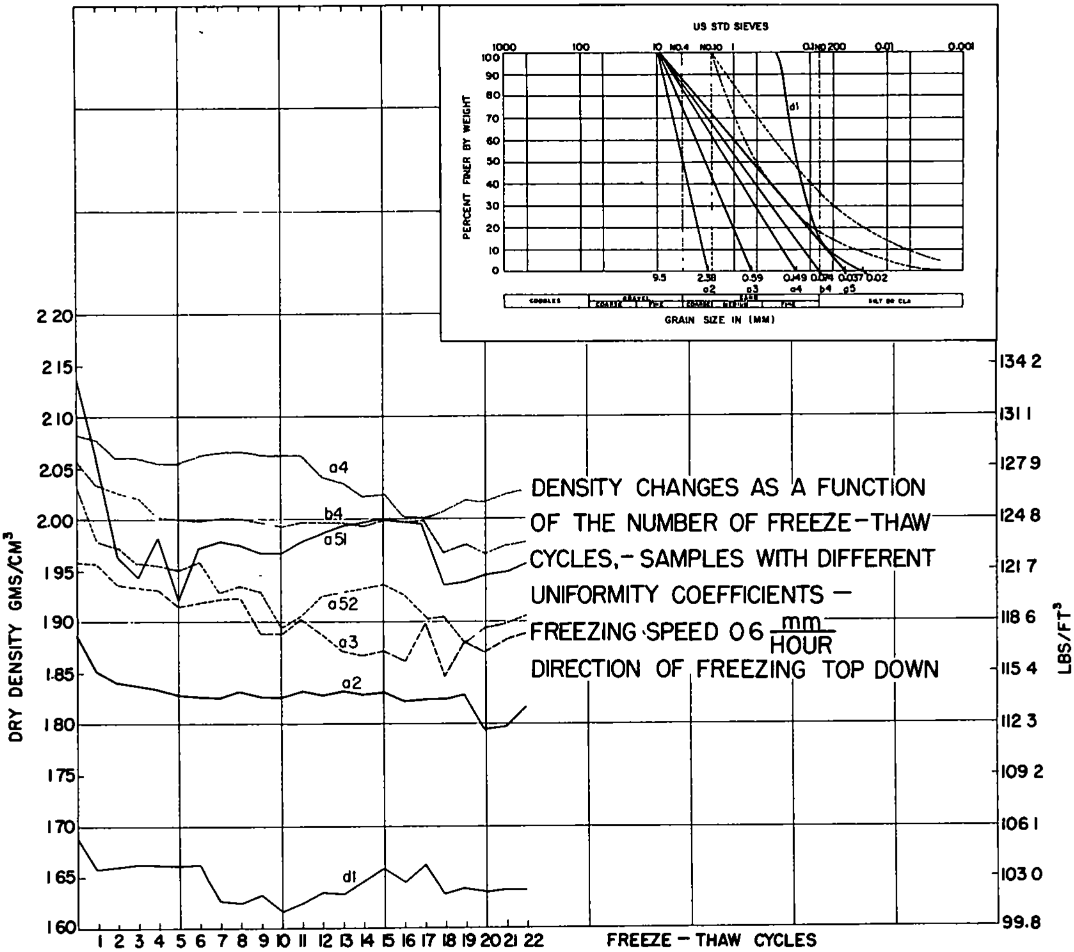


Figure 12.

frost susceptible" according to present engineering standards. Because of space available in the freezing cabinet, another sample d1 was included (Fig. 6); this is a fine sand with 14 percent finer than 0.037 mm, the fines are also made of silicrete. Samples were compacted according to Table 2.

TABLE 2

Sample	Dry Density (g/cm³)	Dry Density (pcf)
a2	1.888	117.86
a3	1.958	122.23
a4	2.083	130.04
b4	2.059	128.54
a5-1	2.141	133.66
a5-2	2.032	126.85
d1	1.690	105.50

The freezing process was performed as in the previous experiment with a top-down freezing rate of about 0.6 mm per hr, and thawing from the top at about 6.0 mm per hr. As in the preceding experiment no surcharge was applied on the samples. Readings of sample height were taken during and after the freezing process and after the thawing cycle. After the thawing stage, the volume and density were computed (Figs. 11 and 12). It can also be said that the volume changes by freeze-thaw are greater for samples with a larger uniformity coefficient. Sample a2, with the smallest uniformity coefficient, showed no changes after cycle 5. The other samples were still changing as this report was written. For this reason, the time for which samples will remain stationary is not given. Sample a5-2

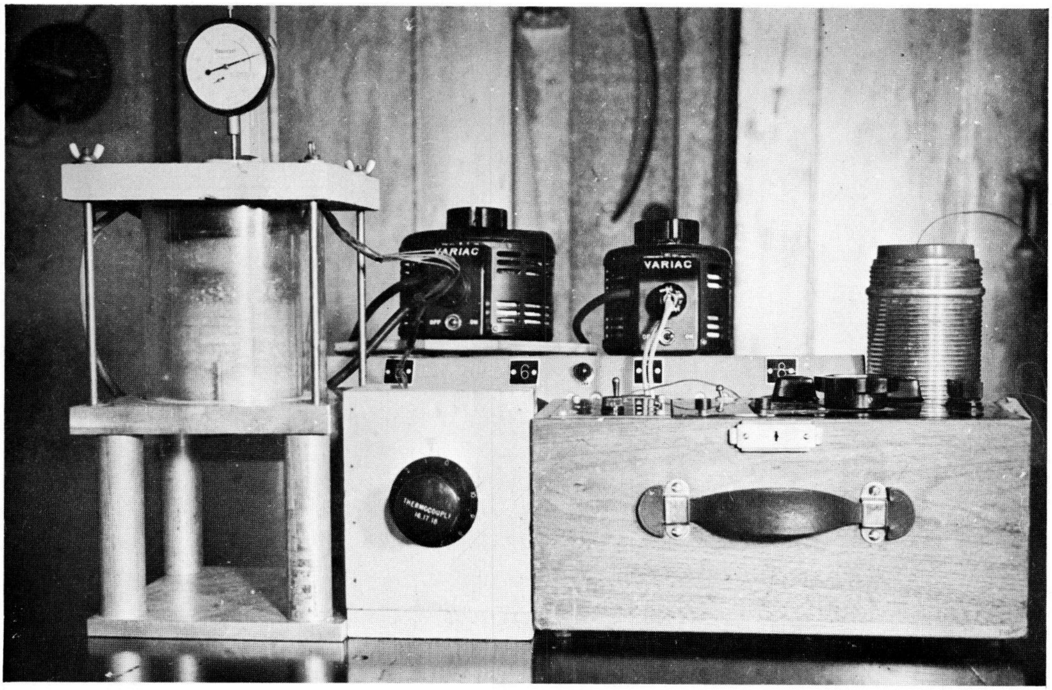


Figure 13. Freezing cabinet which allows a sample to freeze from the bottom upward at different rates of freezing. A heating tape located on wooden top serves to control freezing speed.

changed steadily, with a small gap in cycle 8 until cycle 10, increasing more than 7 percent in volume in 10 cycles; sample a5-1, differing only in the mineralogical composition of the 14 percent finer than 0.074 mm, showed a different volume change (Fig. 11). This indicates that the mineralogical composition of the minus 200 sieve is important in the cyclic freeze-thaw action.

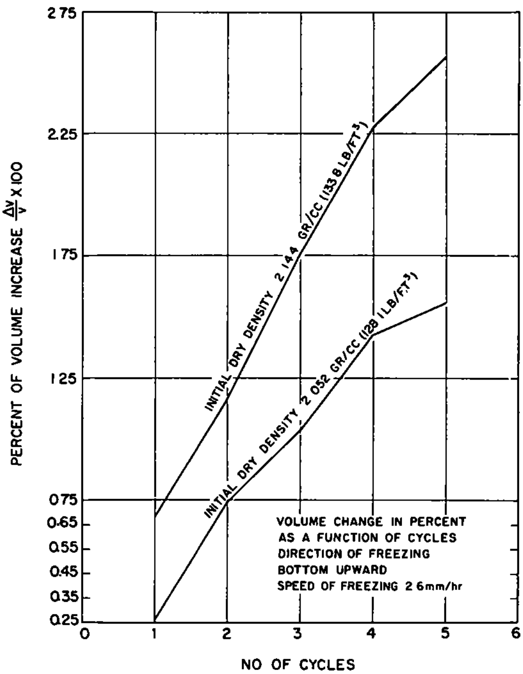
The density and volume changes after 22 cycles are given in Table 3.

TABLE 3

Sample	Dry Density				(C_u)	Volume Increase (%)
	Before Cycling		After 22 Cycles			
	(g/cm³)	(pcf)	(g/cm³)	(pcf)		
a2	1.888	117.86	1.816	113.37	1.9	2.82
a3	1.958	122.23	1.888	117.86	3.8	3.68
a4	2.083	130.04	2.028	126.60	8.5	2.78
b4	2.059	128.54	1.978	123.48	11.3	4.10
a5-1	2.141	133.66	1.958	122.23	16.6	9.31
a5-2	2.032	126.85	1.906	188.99	16.6	6.58
d1	1.690	105.50	1.638	102.26	-	3.20

From this experiment the following can be concluded: Changes in volume are produced in samples considered "non-frost susceptible" by present engineering standards. The changes in volume are greater for samples with a larger uniformity coefficient.

Figure 14.



The Functional Factors of Volume Changes

It has been shown that freeze-thaw cycles produce vertical sorting and changes in soil sample volume. The factors involved in this process are initial density, rate of freezing, and number of freeze-thaw cycles. In this section the effect of such variables on the volume changes and vertical sorting is analyzed. For this test, sample a5-2 was used, with 14 percent passing sieve No. 200 and made of silicrete. A freezing cabinet (called by the author an inverted open system) was used, that allowed the sample to freeze from the bottom upwards (Fig. 13). The bottom-up freezing is produced chiefly by an aluminum plate ¾ in. thick located at the bottom of the sample; by changing the voltage on a heating tape located at the top of the cabinet, different rates of freezing line penetration can be obtained. Thawing was accomplished by increasing the voltage on the top heating tape; in this way a top-to-bottom thawing cycle was produced.

The sample was held in a transparent lucite cylinder 7.5 cm in diameter and 12.5 mm thick, which was enclosed in another cylinder 15 cm in diameter. A 12.5-mm air space between the two cylinders served as an insulator. Through these lucite cylinders the condition of the sample could be observed very clearly. On top of the sample there was an excess of water. This water could be brought down to the freezing plane at different rates, according to the rate of freezing. Several screens were superimposed in the water and the dial gage rested on top of them. No surcharge was applied to the sample.

The sample was placed in the inner lucite cylinder and compacted with a small piston. Two samples with dry densities of 2.144 g per cu cm (133.8 pcf) and 2.053 g per cu cm (128.1 pcf) were prepared. The experiment performed at a rate of freezing of 26 mm per hr demonstrated that the volume and density changes are smaller with a low initial density than with a high initial density (Figs. 14 and 15). The density values are computed for the thawed stage.

Figure 16 shows the density change as a function of the number of freeze-thaw cycles for three freezing speeds: 0.06 cm per hr, 1.2 cm per hr, and 2.6 cm per hr. For a freezing speed of 2.6 cm per hr, the average rate of change in density during the frozen or thawed stage is smaller than that for a freezing speed of 0.06 cm per hr. These values are obtained with an initial density of 2.144 g per cu cm (133.8 pcf).

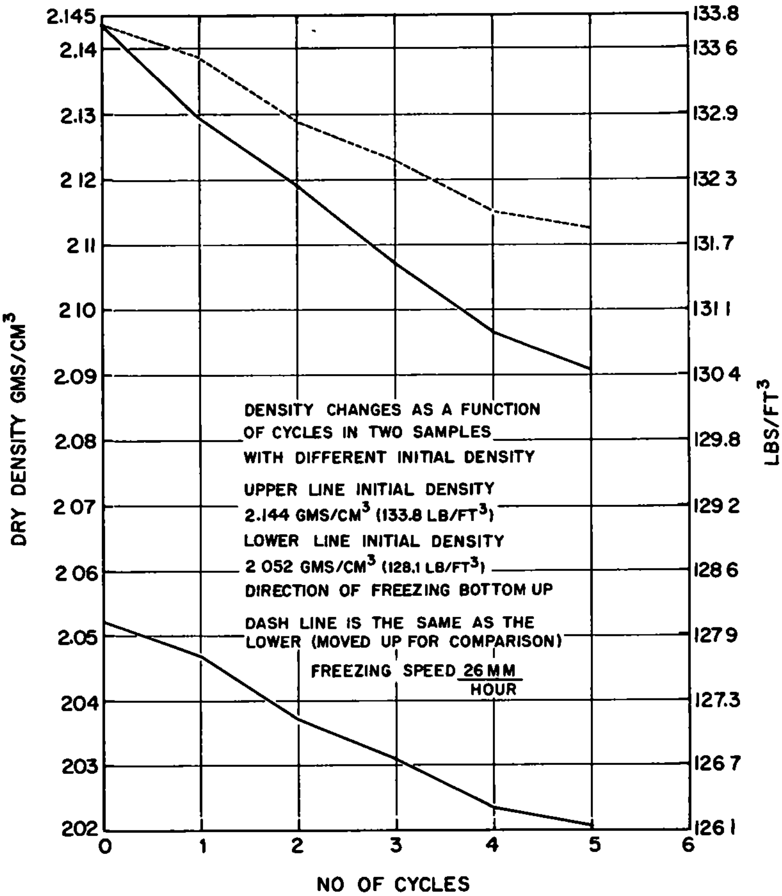


Figure 15.

Because the density changes as a function of cycles and also as a function of the rate of freezing, it is possible to express the density or volume changes as a function of the rate of freezing for different cycles. This was accomplished by subjecting the soil sample with an initial density of 2.144 g per cu cm (133.8 pcf) to 5 cycles of freezing and thawing at three freezing rates: 0.06 cm per hr, 1.2 cm per hr, and 2.6 cm per hr. The results are plotted in Figures 17 and 18. The upper horizontal line on top of Figure 18 shows the initial density. After a first cycle was completed in three samples with the same density and at three freezing speeds, the second cycle was run under the same speeds. Values were obtained for 5 cycles. It is shown that for each cycle the density or volume changes are a function of the rate of freezing. The volume changes are expressed mathematically by the following quadratic equations:

Cycle 1: $y = 3.162 - 1.958X + 0.386X^2$
Cycle 2: $y = 4.147 - 1.91X + 0.295X^2$
Cycle 3: $y = 5.079 - 1.913X + 0.2447X^2$
Cycle 4: $y = 4.847 - 0.38X^2$
Cycle 5: $y = 4.516 + 2.441X - 1.211X^2$

y = volume increase in percent $(\frac{\Delta v}{v} \times 100)$

X = rate of freezing in cm per hour

The density changes are expressed mathematically by the following quadratic equations:

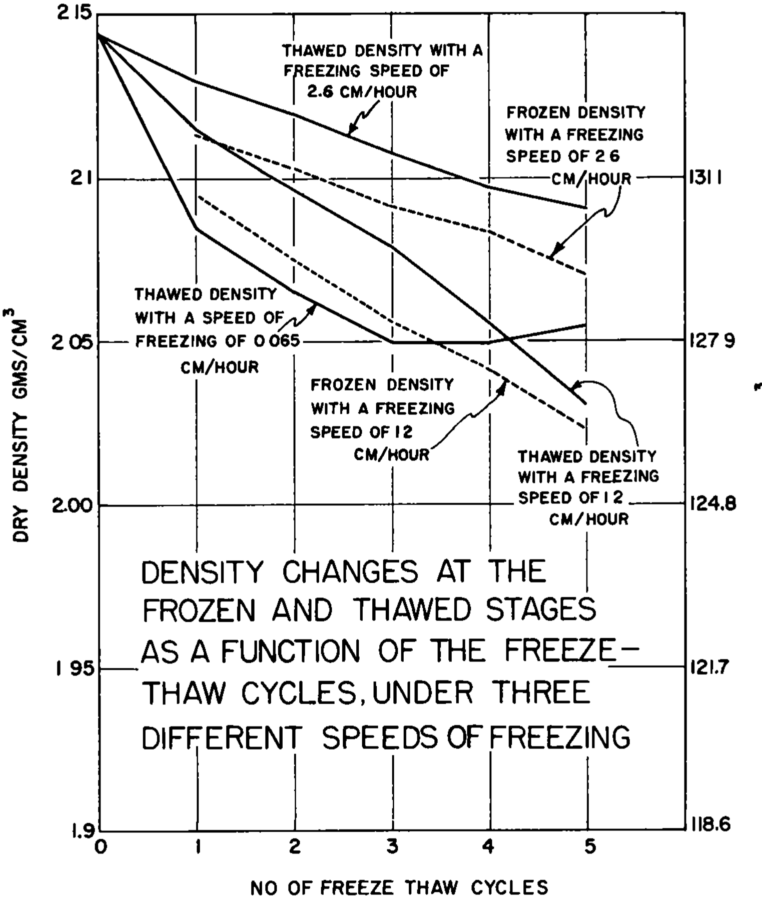


Figure 16.

Cycle 1: $y = 2.0828 + 0.03427X - 0.0062X^2$
Cycle 2: $y = 2.0639 + 0.0315X - 0.00397X^2$
Cycle 3: $y = 2.0471 + 0.02962X - 0.00253X^2$
Cycle 4: $y = 2.0515 - 0.007642X + 0.00953X^2$
Cycle 5: $y = 2.0595 - 0.05568X + 0.02593X^2$

y = density in g per cu cm and pcf
X = speed of freezing in cm per hr

In cycle 5 there is a noticeable drop of volume change and increase in density for low freezing speeds. This can be attributed to the fact the sample becomes so loose that further cycles produce a densification of the loose materials. This can be shown more clearly if volume change is computed as a function of the number of freeze-thaw cycles for different rates of freezing (Fig. 19). The volume changes are small at a high rate of freezing (6.0 cm per hr) and at a low rate (0.06 cm per hr). The drop in volume change after cycle 2 for the rate of freezing of 0.06 cm per hr can be attributed to a compaction stage that is observed in the samples undergoing great changes in volume (see also compaction stage of sample a5-2 after cycles 10 and 19 in Figure 11).

In these experiments it was observed that vertical sorting was not produced under freezing speeds of 6.0 and 3.0 cm per hr. Because freezing speed determines the volume increase at the freezing and thawing stage, it is clear that vertical sorting is a function of density change at the frozen stage.

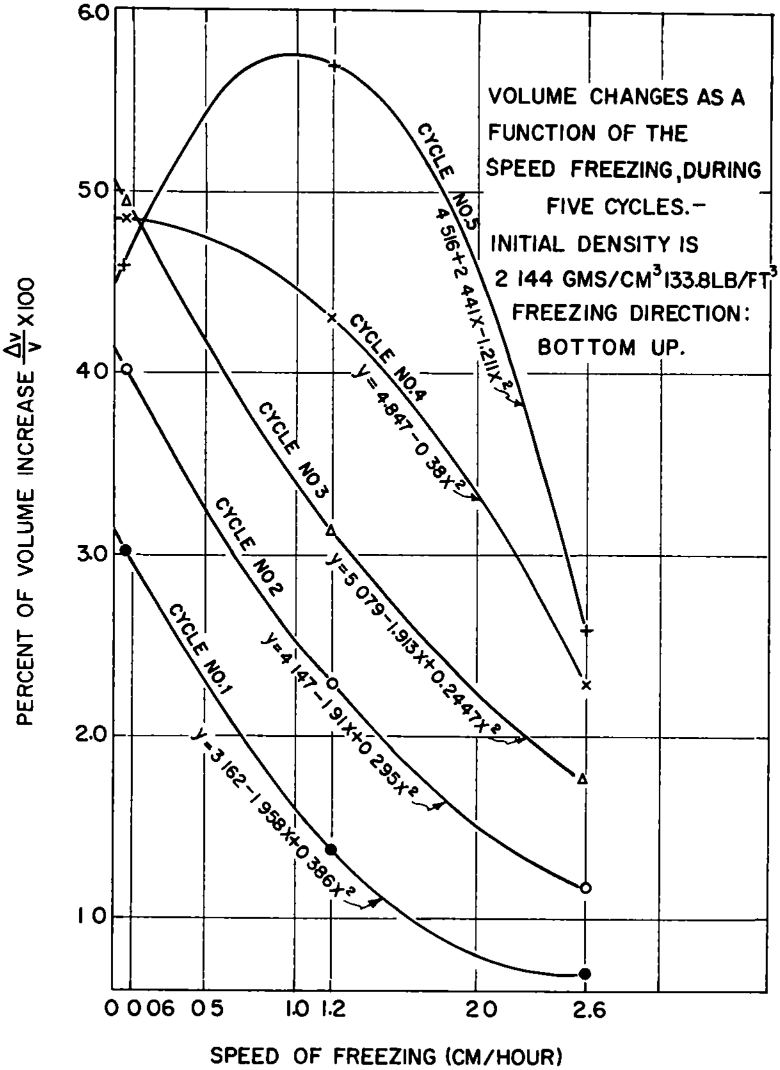


Figure 17.

From these experiments the following can be concluded:

1. The volume changes and vertical sorting of heterogeneous mixture are a function of the speed of freezing and the initial density.
2. Because cycling produces a change in density, the volume changes are functions of the number of cycles.

It has been demonstrated that vertical sorting takes place when freezing and thawing proceeds from the top down. That is the way the upper part of the active layer freezes and thaws.

It is necessary to find out if vertical sorting will be produced by freezing from the bottom up and thawing from the top down, as the lower part of the active layer freezes and thaws.

The sample used for this test is a5-2, in which the 14 percent passing No. 200 mesh is quartz powder. Sample a5-2 was subjected to 7 cycles of freeze-thaw; freezing-line penetration was 1 mm per hr. After the cycling process the sample was separated in

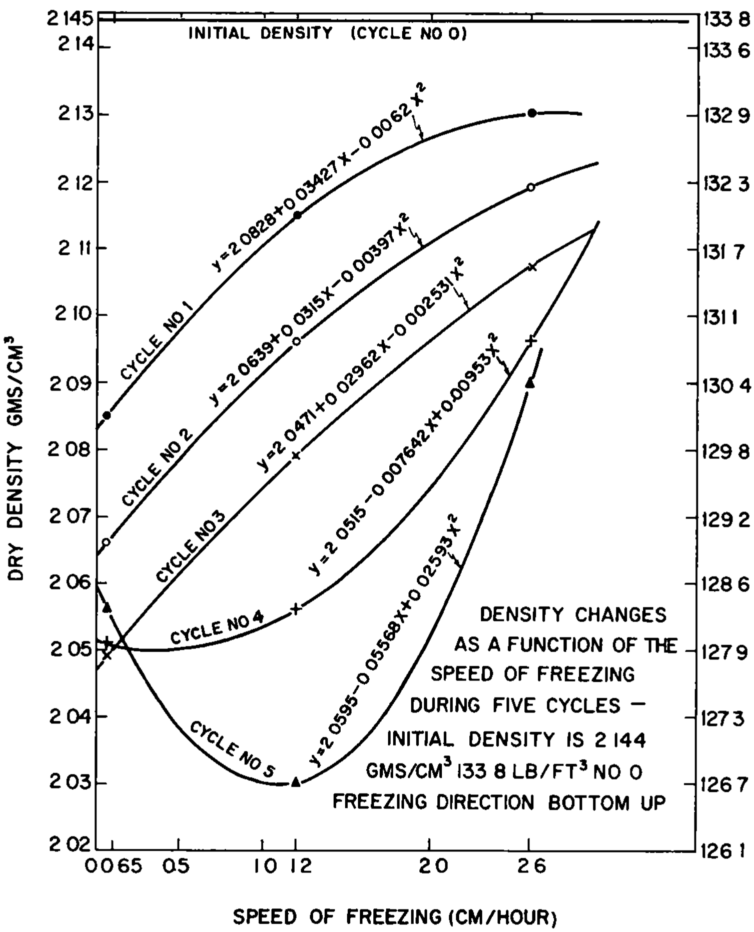


Figure 18.

4 layers. The grain-size analysis shows a clear vertical sorting. Fines have concentrated down at a rate of 0.3 percent per cycle. It will be necessary to carry out more tests under different speeds in order to ascertain the validity of this figure. From this experiment it can be concluded that vertical sorting occurs when freezing proceeds from the bottom at a rate of freezing-line penetration of 1 mm per hr and thawing proceeds from the top down.

Volume Increase by Sorting in Straight Graded Samples Without Freezing and Thawing

One basic question that arises from this sorting phenomenon is: What volume changes will be produced when a mixture of different grain sizes is sorted by mechanical means other than freezing and thawing?

To answer this question, a series of straight graded samples was prepared (Fig. 20). All lines have a common origin of 0 percent at the No. 200 sieve. Samples were prepared according to a straight-line gradation and successive samples had a maximum grain size of ten times the previous one. By increasing the maximum grain size by a multiple of 10 the uniformity coefficient was increased by a multiple of 3.

The procedure for determining the volume changes was the following: the sample was sieved with screen openings differing by a multiple of 2. For example, sample a2 passing ⅜-in. sieve (9.5 mm) and retained on sieve No. 8 (2.38 mm) was separated into two parts by sieve No. 4 (4.76 mm). Sample a3 passing ⅜-in. sieve (9.5 mm) was

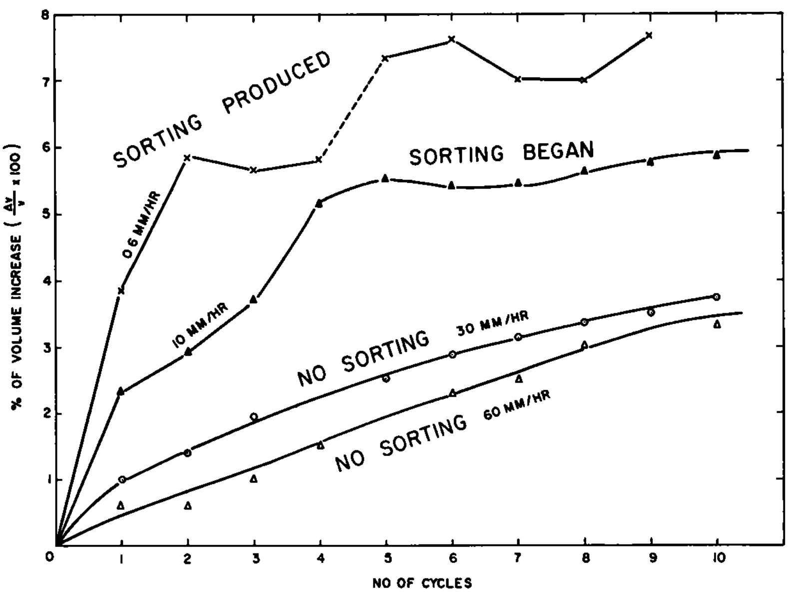


Figure 19. Vertical sorting and relationship between volume increase and number of freeze-thaw cycles, for four rates of freezing.

separated into four fractions retained in sieves No. 4 (4.76 mm), No. 8 (2.38 mm), No. 16 (1.19 mm) and the final fraction retained in No. 30 (0.59 mm). The same procedure was applied in the other samples. In this manner sample a2 was separated into two fractions, a3 into 4, a4 into 6, and a5-1 and a5-2 into 8 fractions. Samples were sieved and each fraction was placed as a layer in a graduated cylinder without compaction and the corresponding percent of volume increase was determined. For an increase in the maximum size of 10 times there is at least a corresponding 10 percent increase in volume by sorting (Fig. 20). Sample 1 with a $C_u = 3.60$ gave 12.5 percent volume change; sample 2 with a $C_u = 11.53$ gave 23.9 percent of volume change; and sample 3 with a $C_u = 37.25$ gave 31.8 percent of volume change. It can be predicted that a sample like 4 in Figure 20 will give more than a 40 percent volume change.

Samples a2, a3, a4, b4, and a5-1 shown in Figure 6 were also sieved in the same sequence of sieves openings shown in Figure 20. The volume changes follow the same pattern as before. The values obtained are presented in Table 4.

TABLE 4

RELATIONSHIP BETWEEN UNIFORMITY COEFFICIENT AND VOLUME CHANGES BY SIEVING

Sample	Uniformity Coefficient (C_u)	Vol. Changes by Sieving ($\frac{\Delta v}{v}$ x 100)
1	3.60	12.5
2	11.53	23.9
3	37.25	31.8
a2	1.9	2.1
a3	3.8	14.0
a4	8.5	20.8
b4	11.3	26.5
a5-1	16.6	31.2

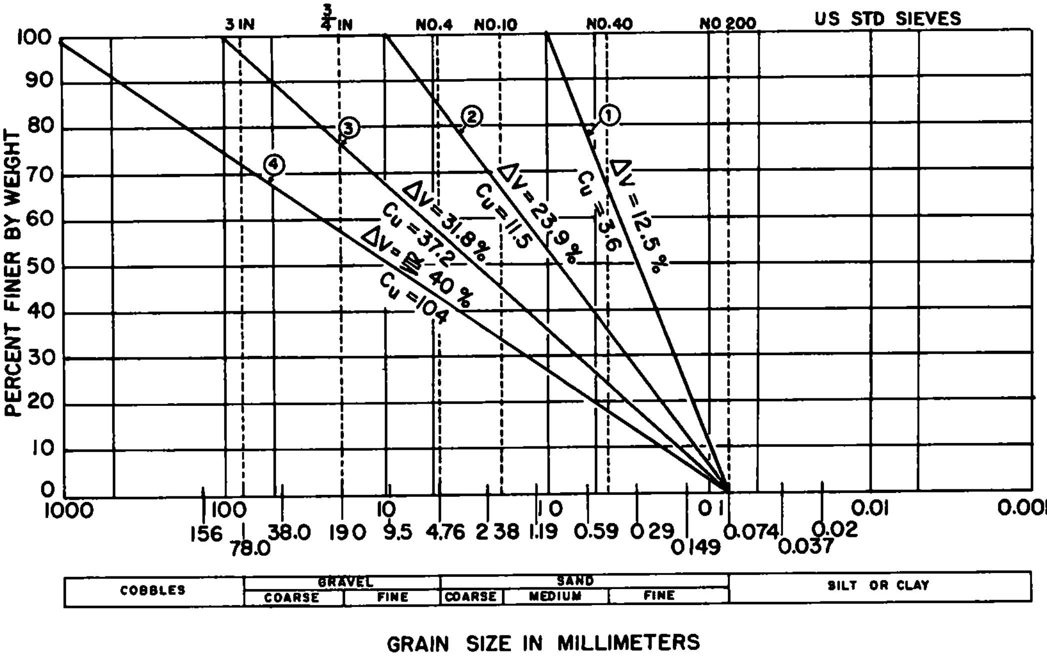


Figure 20. Relationship between uniformity coefficient $C_u = (\frac{D60}{D10})$ and volume changes in straight line graded series.

This table shows that by increasing the uniformity coefficient of a sample the volume changes are also increased. Figure 21 shows the data on volume changes as a function of the uniformity coefficient plotted on semilog paper. A good correlation can be ob-

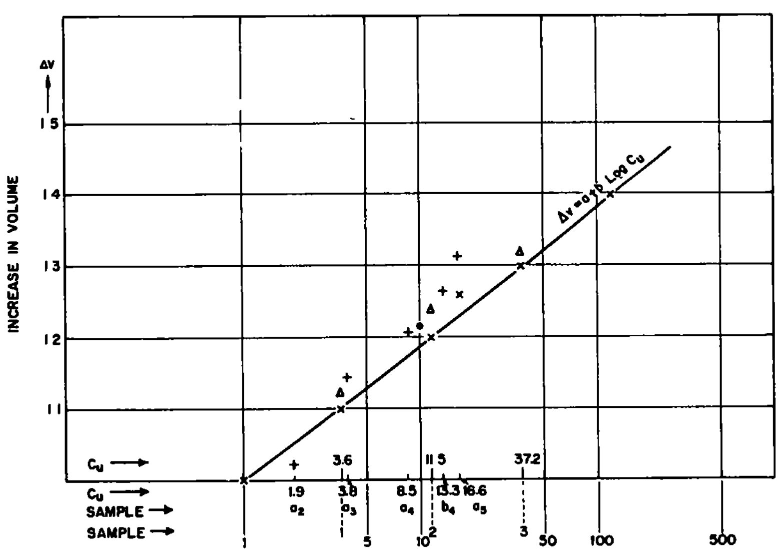


Figure 21. Relationship between volume changes $\frac{\Delta v}{v}$ and $C_u = (\frac{D60}{D10})$ by sorting.

Figure 22. Plain at border of ice cap, Thule area; active layer in lower left removed to deeper level than at foot of trench wall. Active layer also removed in middle background (white areas). Coarse particles near barrel put there by excavation.

served. The solid straight line is the line of the 10 percent volume increase when the maximum size is increased 10 times. It indicates that the volume change is a simple function of the uniformity coefficient. If the gradation of the sample is linear,

$$\Delta v = a + b\ (\log C_u)$$

in which

$$\Delta v = \text{volume increase}$$

$$C_u = \left(\frac{D_{60}}{D_{10}}\right)$$

$$\Delta v = 1.000 + 0.19075\ (\log C_u).$$

If the gradation line is not straight, this relationship will not hold.

The following can be concluded: The volume changes produced by sorting of a heterogeneous mixture is a function of the uniformity coefficient (C_u). An increase in the maximum size of the particles in the mixture by a factor of 10 produces an increase in volume of at least 10 percent.

FIELD DATA

Vertical Sorting of the Active Layer

To establish the validity of the experimental results, it is necessary to find out if the processes in nature agree with the experimental findings. The best data available so far were obtained from the active layer in the Thule area, northwest Greenland. The contractors in the Thule area have been scraping off the active layer in order to obtain construction materials. By following the bulldozers and loaders, an excellent idea of the phenomenon at large can be obtained. Figure 22 shows qualitatively the degree of vertical sorting that has occurred in the area.

A good approach to the phenomenon of vertical sorting (8) was obtained from several hundreds of yards of excavation made in the active layer during the summers of 1956 and 1957. It was noted that the active layer showed vertical sorting when the fraction finer than 0.074 mm was more than 3 percent. Taylor (7) pointed out that even finer active layers show vertical sorting. It was observed that such active layers were in higher places where water could not accumulate. With the experimental information available, it was predicted that coarse active layers should show vertical sorting if they are or were flooded.

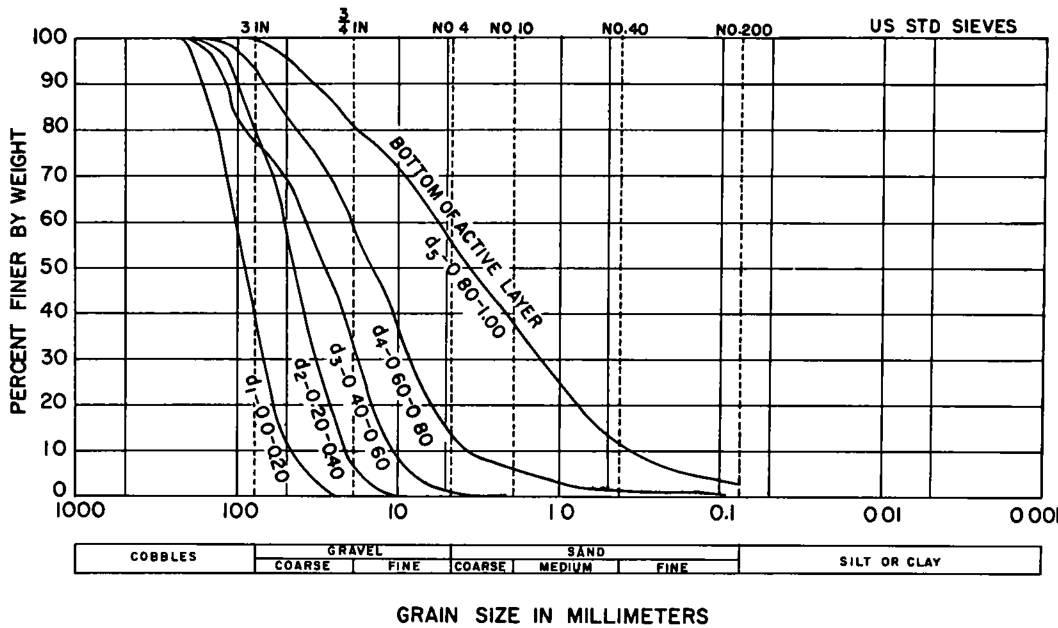


Figure 23. Vertical sorting in active layer, Thule area. Each curve corresponds to 20-cm analyzed layer.

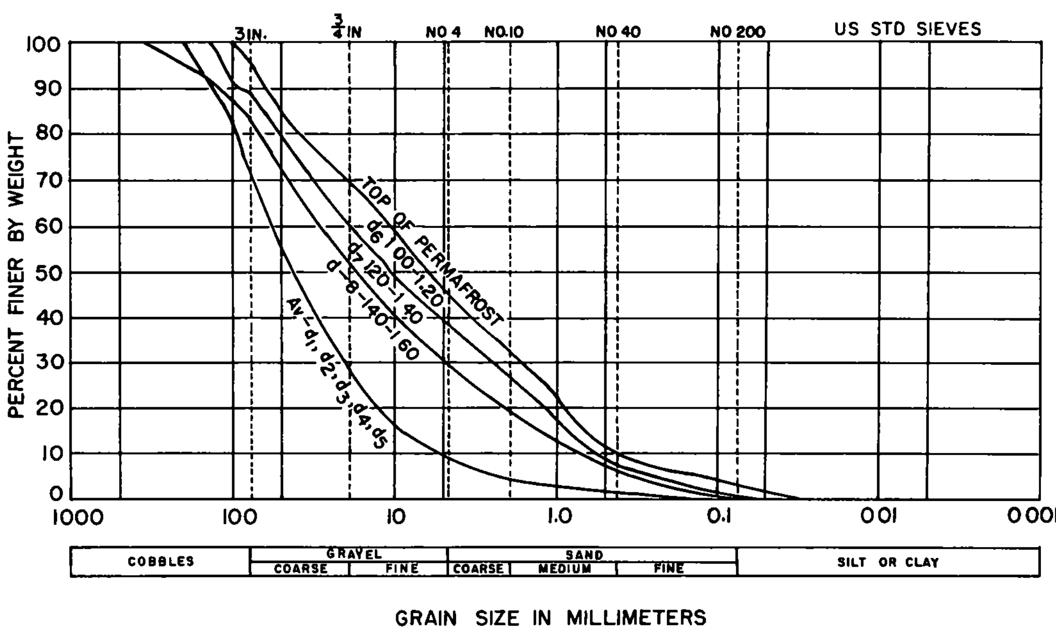


Figure 24. Reverse of vertical sorting.

During 1960, excavations were made in lower areas where water was abundant. A large trench was cut with a bulldozer in order to drain the melt water. Samples were

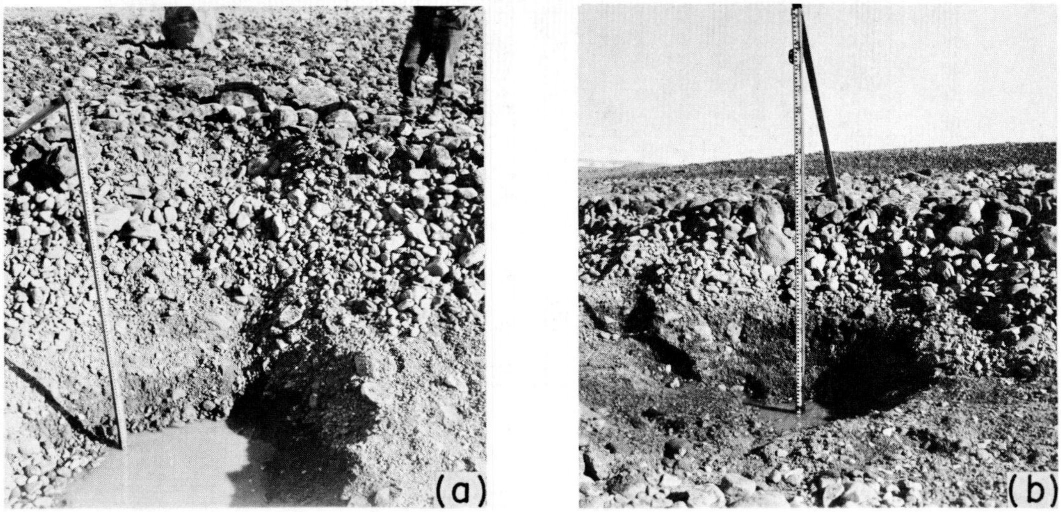


Figure 25. (a) Vertical sorting in active layer, Thule area. Scale rests about 20-30 cm below permafrost table. (b) Scale rests on permafrost.

Figure 26. Vertical sorting on slopes, Thule area. Scale rests on ice wedge in permafrost. Coarse particles below shovel, cave in trench.

taken at regular intervals from the top to the bottom of the active layer and permafrost, and sieve analyses were made (Figs. 23 and 24). It was observed, in general, that a perfect filter system was established in the active layer (Figs. 25 and 26). Entering into the permafrost, the soil gets more and more coarse, tending towards the same gradation as the average of the active layer (Fig. 24). Computation of the volume changes (Fig. 20) shows that a sample with a uniformity coefficient between 30 and 40 will give volume changes of more than 30 percent. For a sample like d8 (Fig. 24) with a $C_u = 30$, a volume change of over 30 percent is expected. Considering that in nature the sorted materials might have a higher degree of compaction than that obtained in the laboratory, an arbitrary one-third of this value can be taken off, and the resulting theo-

Figure 27. Vertical sorting around islands or centers of fines on gentle slope.

retical increase in volume is still 20 percent. This would mean that originally this active layer was 100 cm thick and that sorting has increased it to 120 cm. Another factor that might promote vertical sorting in nature is the washing by streams and rain action especially after thaw when the soil is loose. In the laboratory experiments, samples tested were also washed with water to a degree simulating 1.000 mm of rainfall and without freezing; no vertical sorting was developed. Several other trenches cut in the active layer showed the establishment of the filter system. The perfection of the filter system will depend on the original grain-size distribution as well as the amount of moisture available. When the amount of fines in the active layer increases, then vertical sorting occurs everywhere, even in slopes (Fig. 26). However, when the amount of fines is predominant then the coarser particles behave as if floating in a plastic medium without being able to reach the surface (8). When the active layer contains about 10 percent of particles finer than the No. 200 mesh, the fines are reaching the surface as small islands surrounded by the coarser particles. In these islands as well as outside of them, vertical sorting is present (Fig. 27).

The following conclusion can be made: Vertical sorting is observed in well-graded materials with and without fines (0.074 mm fraction) if they are or were saturated.

Correlation Between Laboratory and Field Data

The laboratory experiments were conducted with rates of freezing similar to those operating in nature. Freezing and thawing proceeded from the top downward, simulating the natural freeze-thaw conditions of the upper part of the active layer. In other experiments freezing from the bottom up and thawing from the top down simulated conditions in the lower part of the active layer. Vertical sorting occurred under both of these conditions.

Another aspect that has to be considered is the effect of loads on the sample. These experiments were performed without surcharge on the sample, but the upward freezing of the active layer occurs under the total load of the active layer. This indicates that vertical sorting will be produced even under load. The average in-place dry density of the soils of the active layer was about 2.0 g per cu cm (124.8 pcf). Assuming a thickness of 100 cm for the active layer, a load of 200 g per cu cm (373 pcf) can be assumed. This indicates that vertical sorting can take place under loads of 200 g per sq cm (373 pcf).

Laboratory experiments and field studies demonstrated that fine particles move downward and coarse ones move upward. Any coarse particle located in the middle of the layer will act as an "umbrella" for the fines that are moving down. That is the reason why there is a concentration of fines on top of the big particles and a lack of fines at the bottom (8). The presence of coarse particles under the stones observed by Vilborg (6) is a part of the process of sorting.

CONCLUSIONS AND RECOMMENDATIONS

Laboratory experiments and field studies indicate that there is a tendency for a heterogeneous mixture of grains to become vertically sorted under repeated freeze-thaw action, when adequate moisture is present, thereby increasing the volume of the mixture this phenomenon is observed when the freezing-and-thawing plane moves from the top or from the bottom. The equilibrium condition of this process is reached when a continuous filter system is established, at least to the degree to which this is possible for any given gradation. This vertical sorting occurs in well-graded materials with and without particles finer than 0.074 and 0.02 mm.

This sorting process is not stopped by a surcharge equal to the load of an active layer with a thickness of at least 1 m or 200 g per sq cm (396 pcf). The fact that particles moved upward as a result of freezing and thawing from the top indicates that vertical sorting must take place in heterogeneous seasonally frozen soils outside the permafrost areas if adequate moisture is available.

This research indicates that particles migrate under freezing and thawing cycles and that this migration is accompanied by changes in the volume of the soil. It is therefore recommended that the engineering significance of such phenomena be considered.

This research also shows that changes in volume produced by freeze-thaw cycles are functions of the heterogeneity of the grains in the soil. Because the uniformity coefficient of the materials varies within short distances, this principle provides a good tool for the understanding of the mounds formed in the active layer and the sorting associated with them.

It was considered important, as a first step, to determine if particles move, and this objective has been accomplished at this stage of the research. The problem of how these particles move will be treated in a separate paper. The following problems are recommended for investigation:

1. The volume changes and sorting produced when the freezing plane in the soil is vertical instead of horizontal.
2. Volume changes and sorting under different surcharges.
3. Pressure exerted by the upward migration of a particle.
4. The effect of particles' sphericity on the segregation process.
5. Sorting produced in nature when the freezing line penetrates from the top down and thawing from the top down and bottom up; in other words, in seasonally frozen areas.

ACKNOWLEDGMENTS

The present report was done under contract DA-11-190-ENG-118 with the Department of the Army for basic investigations in permafrost and annually frozen areas (SIPRE task 0.22.01.041, Field and Laboratory Study of Patterned Ground).

The author is greatly indebted to the U.S. Army Snow Ice and Permafrost Research Establishment (USA SIPRE)* for assistance and cooperation in the research. Special thanks are due to the Technical Director, W.K. Boyd, who encouraged the early stages of the research, the Special Assistant (Technical) to the Director, F.J. Sanger, and the Chief of the Basic Research Branch, J.A. Bender.

*Now U.S. Army Cold Regions Research and Engineering Laboratory (CRREL).

The following persons assisted: W. Brulc, J. Gallippi, E. Murabayashi, S. Mock. A. Tice, A. Poulin, R. Ramsier, R. Tien and Dr. Y. Yen.

This report has been reviewed and approved for publication by the Office of the Chief of Engineers.

REFERENCES

1. Högbom, B., "Einige Illustrationen zu den Geologischen Wirkungen des Frostes auf Spitzbergen (Some Illustrations of Geological Frost Action on Spitzbergen)." Bull. Geol. Inst. Univer., Upsala, 9:41-59 (1908-09).
2. Hamberg, A., "Zur Kenntnis der Vorgänge im Erdboden beim Gefrieren und Auftauen sowie Bemerkungen über die Erste Kristallisation des Eises in Wasser (A Study of Soil Freezing and Thawing Processes and Remarks on the Initial Crystallization of Ice in Water)." Geol. Foren. Forhandl., 37:538-619 (1915).
3. Hesselman, H., "Om Forekomsten af Rutmark pa Gotland (The Occurrence of Polygon Fields in Gotland)." Geol. Foren. Forhandl., 37:481-492 (1915).
4. Beskow, G., "Erdfliessen und Strukturboden der Hochgebirge im Licht der Frosthebung (Solifluction and Structural Soils of the High Mountains with Respect to Frost-Heaving)." Geologiska Foreningens Forhandlinger, 52:622-638 (1930).
5. Troll, C., "Strukturboden, Solifluktion und Frostklimate der Erde, (Structural Soils, Solifluction, and Frost Climates of the Earth)." Geol. Rundschau, 34: 545-694 (1944).
6. Vilborg, L., "The Uplift of Stones by Frost." Georgrafiska Annaler, 37:164-169 (1955).
7. Taylor, R.S., "A Study of Some High-Latitude Patterned-Ground Features." Univer. of Minnesota, Ph. D. Thesis (1956).
8. Corte, A., "Relationship Between Four Ground Patterns, Structure of the Active Layer and Type and Distribution of Ice in the Permafrost." U.S. Army Snow Ice and Permafrost Research Establishment, Corps of Engineers, Research Report 88 (1959) (in preparation).
9. Taber, S., "The Growth of Crystals Under External Pressure." Amer. Jour. Sci., Fourth Ser., 191: no. 246, 532-556 (1916).
10. Taber, S., "Surface Heaving Caused by Segregation of Water Forming Ice Crystals." Eng. News-Record, 81:683-684 (1918).
11. Taber, S., "Ice Forming in Clay Soils Will Lift Surface Weights." Eng. News-Record, 80:262-263 (1918).
12. Taber, S., "Freezing and Thawing of Soils as Factors in the Destruction of Road Pavements." Public Roads, 11:113-132 (1930).
13. Taber, S., "The Mechanics of Frost Heaving." Jour. Geol. 38:303-317 (1930).
14. Casagrande, A., "Bodenuntersuchungen im Dienste des Neuzeitlichen Strassenbauses (Soil Investigations for Modern Road Construction)." Strassenbau, 25:25-28 (1934).
15. Dücker, A., "Ist das Mass der Frost-Hebung Unabhängig von der Temperatur? (Is the Degree of Frost Heaving Independent of Temperature?)." Die Strasse 4:138-140 (1937).
16. Dücker, A., "Untersuchungen über die Frostgefährlichen Eigenschaften Nichtbindiger Böden (Investigations on the Frost-Susceptible Properties of Cohesionless Soils)." Forschungsarbeiten aus dem Strassenwesen, Volk u. Reich Verlag, Berlin, Vol. 17 (1939).
17. Dücker, A., "Ueber Boden Kolloide und Ihr Verhalten bei Frost (Soil Colloids and Their Behavior When Subjected to Frost Action)." Bauingenieur, 23:235-237 (1942).
18. Dücker, A., "Gibt Es eine Grenze Zwischen Frostsicheren und Frostempfindlichen Lockergestein? (Is There a Limit Between Frost Resistant and Frost Susceptible Loose Soil Materials?)." Strasse u. Autobahn, 6:78-82 (1956).
19. Tsytovich, N.A., "The Fundamentals of Frozen Ground Mechanics (New Investigations)." Proc. Intern. Conf. Soil. Mech. Found. Eng., 4th Conf., London, 1:116-119 (1957).

20. Kersten, M., "Thermal Properties of Soils." Bull. Univer. Minn. Inst. Technol. Eng. Exp. Sta. Bull. 28, Vol. 52, No. 1 (1949).
21. Kersten, M., "Laboratory Research for the Determination of the Thermal Properties of Soils." Final Report, Univer. Minn. Eng. Exp. Sta. (1949).
22. Penner, E., "The Mechanism of Frost Heaving in Soils." HRB Bull. 225, 1-22 (1959).
23. Jumikis, A., "The Frost Penetration Problem in Highway Engineering." Rutgers Univer. Press (1955).
24. Martin, R.T., " Rhythmic Ice Banding in Soil." HRB Bull. 218, 11-23 (1959).
25. Higashi, A., "Experimental Study of Frost Heaving." U.S. Army Snow Ice and Permafrost Research Establishment, Corps of Engineers, Research Report 45 (1958).
26. Cass, L.A., and Miller, R.D., "Role of the Electric Double Layer in the Mechanism of Frost Heaving." U.S. Army Snow Ice and Permafrost Research Establishment, Corps of Engineers, Research Report 49 (1959).
27. Low, P.F., and Lovell, C.W., "The Factor of Moisture in Frost Action." HRB Bull. 225, 23-44 (1959).
28. Lindell, K.A., and Kaplar, C.W. "The Factor of Soil and Material Type in Frost Action." HRB Bull. 225, 81-128 (1959).
29. Woods, K.B., "Discussion of 'The Factor of Soil and Material Type in Frost Action' By K.A. Linnell, and C.W. Kaplar." HRB Bull. 225, 126-127 (1959).
30. Schmertman, J.H., "A Thermally Controlled Soil Freezing Cabinet." U.S. Army Snow Ice and Permafrost Research Establishment, Corps of Engineers, Technical Report 50 (1958).
31. Schaible, L., "Ueber die Zunehmende Gefahr der Frostschäden für Unsere Verkehrswege (Increasing Danger of Frost Damage to Our Roads)." Bautechnik, 30:262-266 (1953) and 31:287-292 (1954).
32. Waterways Experiment Station, "The United Soil Classification System." Corps of Engineers, U.S. Army Tech. Memo. 3-357 (1953).