ADFREEZING OF SANDS TO CONCRETE

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This paper presents experimental results obtained when the magnitude of the adfreezing force between frozen sands and concrete was investigated under laboratory conditions. Factors influencing the magnitude of the adfreezing force, called frost-grip, are introduced and discussed. Three different sands were used to provide more information relating to the influence of the sand's physical properties—i.e., particle shape, size, and gradation—on the magnitude of frost-grip. A simplified general equation to predict the values of the adfreezing force valid for all three sands is introduced as a function of five parameters.

•IN AREAS subject to temperatures below freezing, "frost-grip" between frozen soil and the material with which it comes in contact is a common occurrence. Researchers studying this phenomenon of frost-grip or adfreezing of soil to foundation units were mainly concerned with its contribution to the possible damage done to structures due to frost heaving (1, 2, 3). Their attention therefore was limited to frost-susceptible soils only. As a consequence, the effect that a frozen soil layer, even when non-frost-susceptible, can have on the stability of retaining walls, foundations, or any other structure was generally overlooked.

To avoid frost heave, non-frost-susceptible granular soils are used by many engineers as a select material in areas subject to frost action. Sandy soil when moist will adhere to concrete surfaces upon freezing. Consequently, this bonding force, referred to as frost-grip, will resist independent vertical movement of the unheated part of any structure or of the frozen soil layer. The frozen sand layer thus bonded to the structure could retard settlement of the unheated part of the structure during the winter months or, in the case of retaining walls, could provide a resisting force that must be overcome before failure of the wall could occur. In the latter case, frost-grip force could counteract the additional overturning force, i.e., the lateral thrust developed in a sand-ice layer due to temperature change that was discussed previously by the author (4, 5). For such cases, the knowledge of the magnitude of the frost-grip (even if obtained under laboratory conditions) and the parameters on which it may depend is of considerable importance and therefore was the main purpose of this investigation.

It was suspected that the magnitude of frost-grip that could be developed by frozen granular soils would be mainly the function of the following parameters: ice content, porosity, temperature, and particle shape, size, and gradation. Experiments were carried out to obtain comparable values of the frost adhesive force between frozen sands and concrete surfaces for various combinations of these variables. Three different sands were used in the investigation to provide more information relating to the effect of particle size, shape, and gradation. To avoid the effect of time-dependent creep or relaxation on measured frost-grip, the rupture strength developed between soil and concrete was measured under rapid loading. It is beyond the scope of this paper to also include the long-term loading effect on the magnitude of the adfreezing force, and therefore the frost-grip discussed represents the instantaneous adhesive force measured under rapid loading.

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SOILS STUDIED

Three different types of sand were used in the experimental investigation. Sand No. 1 was a crushed uniform sand from Ottawa, Illinois (uniformity coefficient 1.5 and specific gravity 2.65). Sand No. 3 was a natural variety of well-graded sand from Paris, Ontario (uniformity coefficient 3.8). Sand No. 2 (uniformity coefficient 2.85) was obtained from sand No. 3 mainly by eliminating the soil grains larger than 3.3 mm and smaller than 0.104 mm. Specific gravity for both sands No. 2 and No. 3 was virtually the same, 2.67. The grain size distributions are shown in Figure 1.

EXPERIMENTAL TECHNIQUE AND PROCEDURE

The experimental technique for measuring the frost-grip between the sand-ice system and concrete was as follows: The known weight of dry sand and required amount of water were thoroughly mixed together to give the desired water content of 5, 10, or 15 percent. The prepared soil was then placed in the hollow core of a concrete mold, shown in Figure 2, and compacted in the majority of cases by a manually operated standard Proctor hammer. The concrete molds were moistened before the specimens were compacted into them. To obtain a porosity range as wide as possible, the compaction effort was varied from zero blows (the soil being pushed in by a trowel and gently pressed by a mallet) to 50 blows (each of 5 layers being struck 10 times by a standard Proctor hammer). Further decrease in porosity was achieved by subjecting some of the specimens to vibration; this procedure was chosen because it eliminated the possible crushing of the sand particles under an increased compaction effort. During compaction, representative soil samples were taken from each mold for the purpose of determining the water content.

It has been indicated by Tsytovich (6) that in granular soils unfrozen water content is negligible; therefore, the ice content in each frozen specimen was assumed to be equal to its water content measured before freezing took place. Degree of ice saturation, however, was based on 9 percent volume expansion of the pore water upon freezing.

When preparing specimens for a high degree of ice saturation, a layer of heavy waxed paper was glued to the bottom of each mold to prevent water loss from the sand samples. The temperature of each sample was measured by means of two copper-constantan thermocouples placed in the specimen at two different levels—1 in. (2.54 cm) below the top surface and 1 in. from the bottom—and connected to the potentiometer through a multipolar rotary switch.

The filled molds were placed in the freezing chamber along with steel punch-out plates, and after completion of the necessary wire connection to the temperature potentiometer the specimens were frozen to the required temperature.

While in the freezer only the top of each soil sample was exposed to the atmosphere; the sides of each concrete mold were insulated and the bottom rested on a $1\frac{3}{4}$-in. (4.5-cm) thick wooden board covered with a layer of heavy waxed paper. Under these conditions, the specimens were subjected to unidirectional freezing, since the wooden board acted as insulation. The bottom insulation of soil samples changes the freezing pattern from that existing in nature because it prevents the upward flow of heat and moisture toward the cold front. All sands investigated were subjected to the same freezing pattern, and therefore comparable sand-ice specimens were obtained. Furthermore, the "closed" system used permitted easy preparation of the samples with the desired ice content, one of the most important parameters influencing the magnitude of frost-grip.

Before each test, the frozen samples were left at a selected constant temperature for not less than 6 hours to ensure uniform temperature distribution throughout the frozen sand-ice specimens. After that, specimens were removed from the freezer and placed in the compression tester one at a time. They were loaded quickly to avoid excessive plastic flow; the selected constant rate of induced deformation was 0.05 in./minute (0.12 cm/minute). This rate of loading corresponds to ASTM test method D 1633-63, recommended for determining the compressive strength of molded soil-cement cylinders. The ultimate force required to free the sand-ice core from the concrete mold was recorded; this, when divided by the surface contact area between specimen and concrete (measured at the time of failure), gave the frost-grip. It was observed that the decrease in height experienced by the sand-ice specimen during testing rarely exceeded 0.1 in. (0.25 cm).

Figure 1. Grain size distribution.

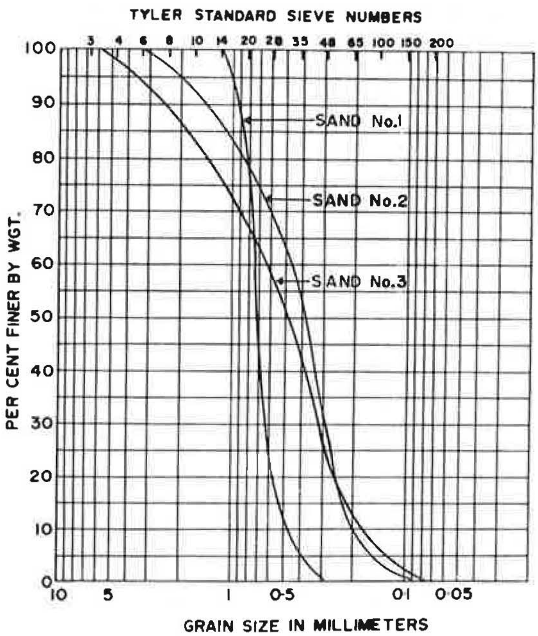


Figure 2. Dimension of molds and schematic testing arrangement.

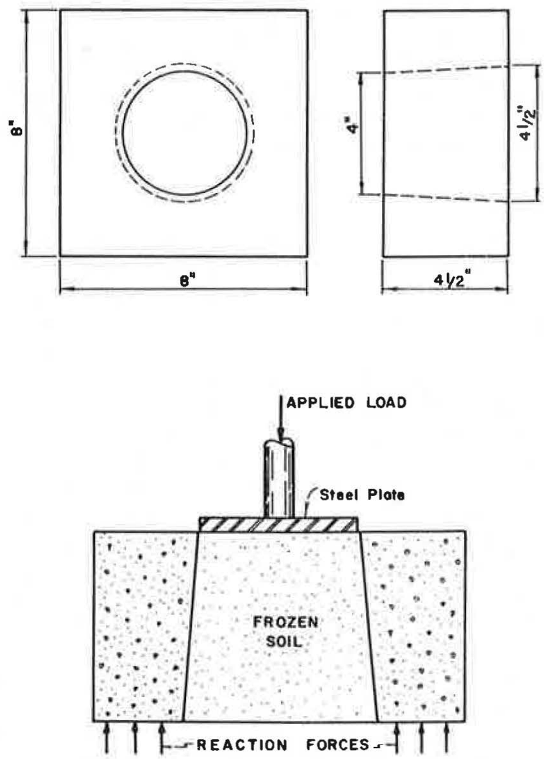


Figure 3. Frost-grip versus porosity for 5, 10, and 15 percent ice content: Sand No. 1, temperature 0 F.

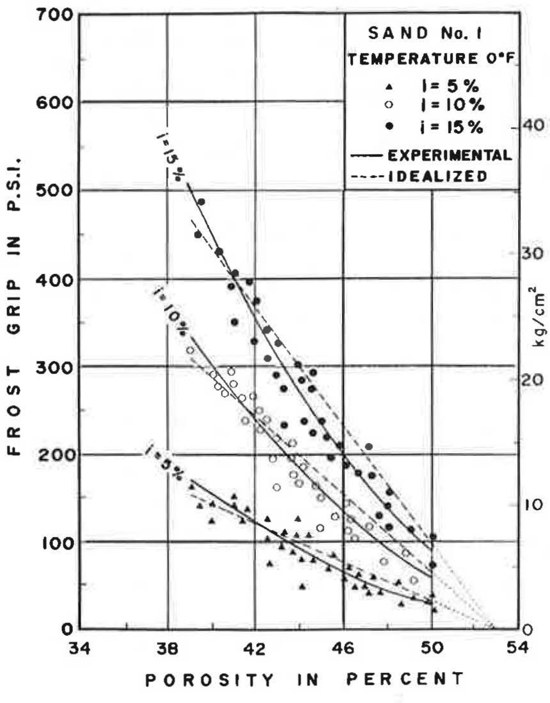
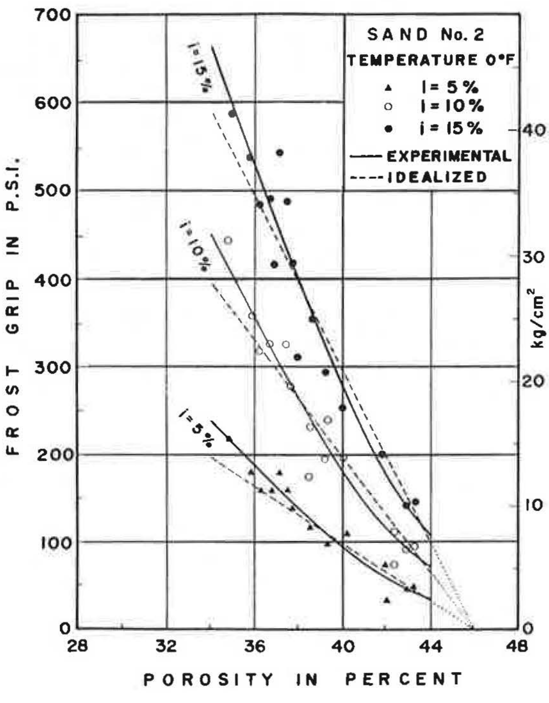


Figure 4. Frost-grip versus porosity for 5, 10, and 15 percent ice content: Sand No. 2, temperature 0 F.



At this point it should be mentioned that the vertical deformation of 0.1 in. would reduce the effective frozen sand-concrete contact area by only 2 percent.

The molds were made of a rich concrete mix for increased strength and durability; the proportions were 1 part cement, 1 part sand, and 1 part ⅜-in. (0.95-cm) crushed stone, with water added to give good workability. This mix provided a compressive strength of over 5,000 psi (34 500 kPa), using 3 in. × 6 in. (7.6 cm × 15 cm) test cylinders cured under water at room temperature for 28 days. No mold was used more than ten times, to preserve uniformity in the roughness of the concrete surface.

DISCUSSION OF RESULTS

Experimental results confirm that the parameters under investigation, namely, the sand porosity, n; ice content, i; temperature, T; and type of sand (defined by its origin; uniformity coefficient, U; and particle shape and size), have a significant effect on the magnitude of the adfreezing force, F. Graphs were plotted to obtain the relationship between these individual variables and frost-grip.

Figures 3 through 6 show the effect of porosity on the magnitude of frost-grip for three different constant values of ice content, i.e., 5, 10, and 15 percent. The type of sand used and the temperature of tested sand-ice specimens are indicated in each figure. All experimentally obtained curves show a rather rapid decrease in frost-grip stress with the increase in porosity. The rate of decrease in frost-grip is the largest at lower levels of the practical porosity range (where the curves are almost straight lines) and the smallest at the other end of the porosity range, where the highest values of obtained porosity are recorded. The nonlinearity shown by the F versus n curves can be attributed partly to the nonlinear change in degree of ice saturation resulting from changes in the sand's porosity under conditions of constant ice content.

Because the porosity in which all sands in nature are found is small, the F versus n curves can be reasonably approximated by straight lines converging at a point on the porosity axis, as shown by dotted lines in Figures 3 through 6. This idealization is done with the view to obtaining a simpler and more easily usable mathematical relationship between frost-grip and the related variables.

The convergence of the F versus n idealized lines at a point on the porosity axis suggests that every investigated type of sand has its own theoretical limiting value of porosity, above which no frost-grip will develop. On the other hand, the experimental curves, if extended to the level of intercept porosity, would indicate some small value of frost-grip. The error resulting from this difference is not important, because in all cases the intercept porosity was found to be outside the practically obtained porosity range.

Figures 3 through 6 also show that an increase in ice content results in a considerable increase in frost-grip for any constant porosity. It can be observed that frost adfreezing stress developed by a frozen sand is directly proportional to its ice content and therefore to its ice saturation. This manifests itself in the fact that at a given constant porosity the vertical distances between experimental curves representing 5, 10, and 15 percent ice content are practically equal.

Figure 7a shows a typical relationship between frost-grip and ice content obtained for three investigated sands all having the same porosity, n = 40 percent, and the same temperature, T = 0 F (-17.8 C). It should be noticed that crushed uniform Ottawa sand, referred to as sand No. 1, developed the largest frost-grip, followed by natural, medium-graded and well-graded sands No. 2 and No. 3 respectively. The combined effect of porosity and ice content on the magnitude of frost-grip obtained for sand No. 1 at the constant temperature of 0 F is shown in Figure 7b.

The three investigated sands, when compared at the same temperature, water content, and porosity, show a significant difference in the magnitude of the frost-grip developed. This leads to the conclusion that the frost-grip between frozen sand and concrete is influenced not only by the ice content (or degree of ice saturation) but also by the physical properties of the sand, i.e., the particle shape, size, and gradation.

When the concrete surface and frozen sand layer are forced to move vertically in respect to each other, it can be expected that not only shearing of the ice adhered to the concrete takes place but also some shear deformations in the sand's mineral skeleton. Therefore, it is not only the ice that comes in contact with the concrete surface that

Figure 5. Frost-grip versus porosity for 5, 10, and 15 percent ice content: Sand No. 3, temperature 0 F.

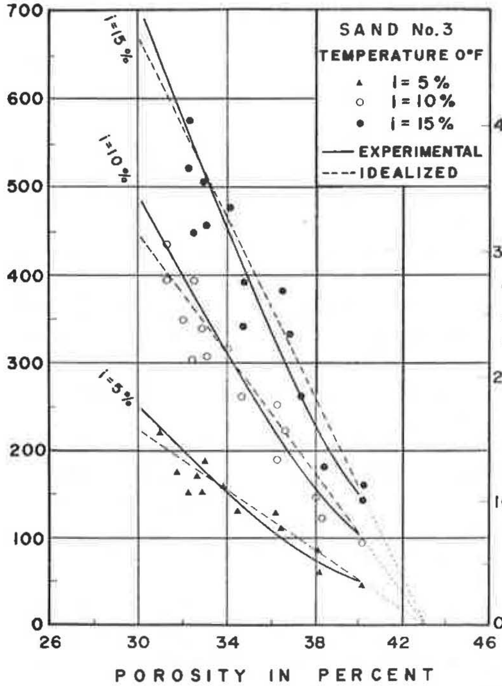


Figure 6. Frost-grip versus porosity for 5, 10, and 15 percent ice content: Sand No. 2, temperature 30 F.

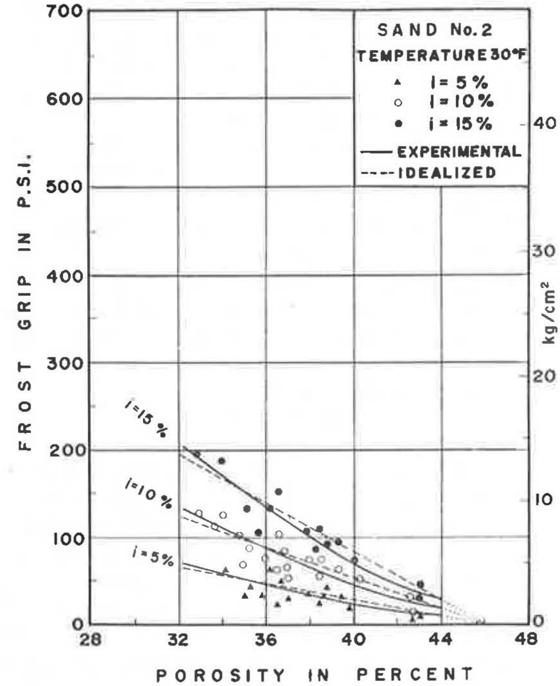
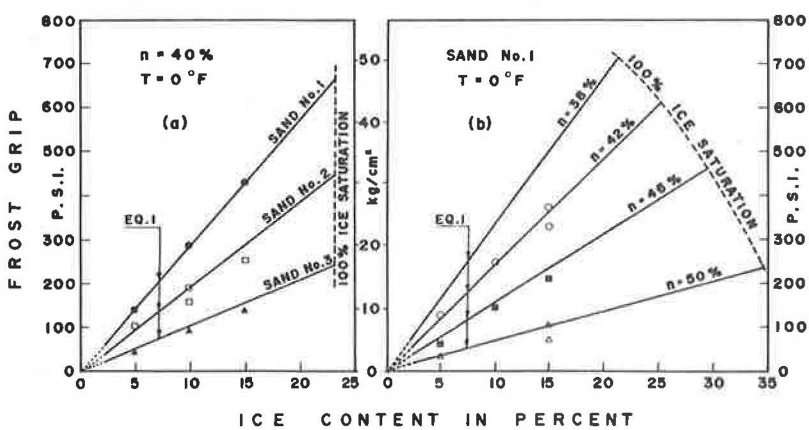


Figure 7. Frost-grip versus ice content: (a) Three investigated sands at porosity 40 percent and temperature 0 F; (b) Sand No. 1 at four different porosities and constant temperature 0 F.



contributes to the frost-grip magnitude but also, to some extent, the ice that binds the sand particles together. Furthermore, in the specific case of sand No. 1, the large number of angular particles lodged in the concrete surface and forced to move while bound by ice contributed to the high results given by that sand. Visual inspection conducted after the testing of the specimens confirmed (especially in the case of sand No. 1) that some sand particles were forced to move or were broken off from the sand-ice surface during the testing.

In general, when comparing at the same porosity any three corresponding F versus n curves (the same temperature and ice content but different sand) shown in Figures 3 through 5, it can be observed that the sand's physical properties—dense packing, angular shape, and uniform particle size—contribute to the high values of frost-grip. On the other hand, loose packing, rounded shape, and nonuniform particle size have the opposite effect on the magnitude of frost-grip.

Figure 8 shows the effects of temperature on the frost adfreezing stress developed by the three investigated sands. The frost-grip increases with a decrease in temperature, the rate of increase being greatest close to the freezing point. The effect of temperature change on the magnitude of frost-grip is more pronounced in sands having a high ice content than in those having a low ice content.

Because the soil pore water increases its volume when converted to ice, it was considered desirable to study the effect that the rigid concrete molds may have on the magnitude of frost-grip, especially when investigating saturated or nearly saturated specimens. Therefore, in addition to the previously described solid samples obtained by packing moist sand into the hollow concrete mold, samples with a vertical hole in the middle and split concrete molds were introduced.

The samples with a hole were obtained by placing vertically in the middle of each mold a flexible rubber tube of 1.25 in. (3.175 mm) outside diameter pulled over an aluminum pipe. The area between the rubber tube and concrete mold was filled with moist sand, the sand was compacted, and the sample was placed in the freezer. Afterwards, the aluminum pipe was withdrawn, and the rubber tube left inside was packed loosely with insulating material. In the case of water-saturated or nearly saturated sands, this created favorable conditions for the possible outflow of excess pore water resulting from water expansion at freezing.

Split samples were obtained by cutting concrete molds in half vertically and placing them individually into a heavy steel frame. An impervious membrane was attached to the bottom and sides of each concrete mold to keep the water inside the sand samples. Two horizontal bolts passing through one side of the steel frame were designed to keep two halves of the mold tightly pressed together during the compaction of the specimen. The bolt pressure on the mold was released in the freezer after freezing of the specimen took place. Later, during testing, the bolts were used to support the concrete mold to prevent free lateral expansion during extraction of the sand-ice core.

The results obtained are shown in Figure 9, which indicates that, as long as the volume of ice formed is equal to or less than the volume of voids in the sand, there is no significant difference between frost-grip values obtained when using solid samples, samples with a vertical hole, or samples tested in a split mold. Therefore, it can be concluded that the rigidity of concrete molds did not influence the magnitude of frost-grip by any significant amount.

FROST-GRIP EQUATIONS

Referring to the idealized F versus n straight dotted lines shown in Figures 3 through 6, the magnitude of frost-grip can be expressed by the general equation

$$F = m\,(N - n) \tag{1}$$

where

F = frost-grip, in psi;
m = slope of the idealized F versus n line representing constant water content, in psi/percent;

Figure 8. Frost-grip versus temperature for three sands having ice content of 5, 10, and 15 percent.

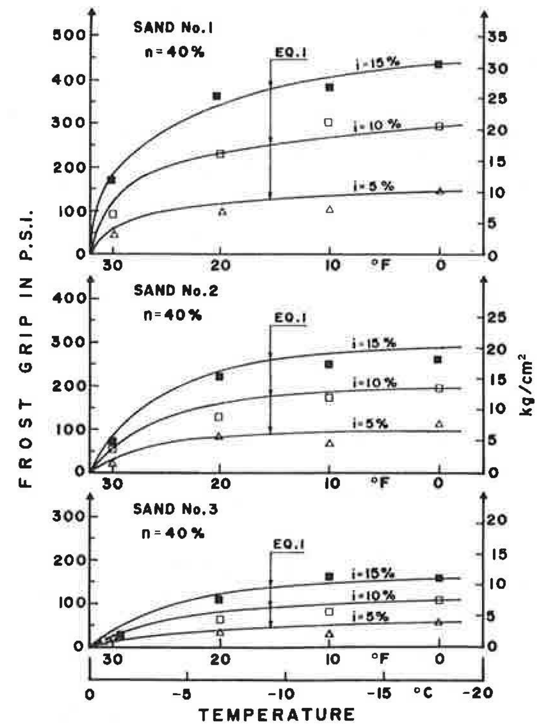
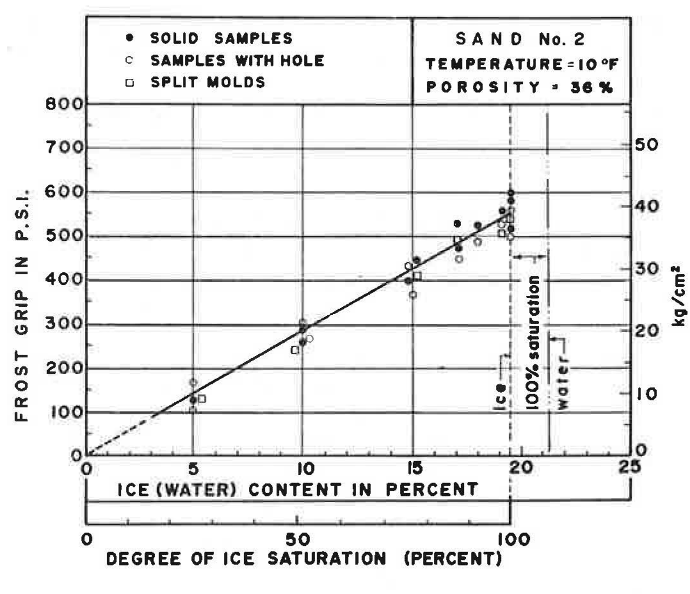


Figure 9. Frost-grip versus water content: Comparison of results using varied techniques.



n = porosity, in percent; and
N = the intercept on the porosity axis at F = 0, referred to as "terminal porosity", in percent.

Based on experimental results, the values of slope m and terminal porosity N can be expressed in the form of the following empirical equations, derived by searching systematically for unknown functions by means of an electronic computer:

$$m = A\, i\, (32 - T)^{0.25} \tag{2}$$

valid for T < 27 F (-2.8 C), and

$$N = (1.0414 - 0.0053 \log_{10} U)^{100} \tag{3}$$

where

A = adfreezing factor, in psi/percent^2;
i = ice content, in percent;
U = uniformity coefficient of sand; and
T = temperature, in deg F.

Values of A and U can be found experimentally for any particular sand. The values of A and U obtained for three investigated sands are as follows:

Sand	Type	A	U
Sand No. 1	Crushed, uniform	0.95	1.5
Sand No. 2	Natural, medium-graded	1.40	2.85
Sand No. 3	Natural, well-graded	1.45	3.8

However, at temperatures near the freezing point, the adfreezing factor A was found to be somewhat lower in value and constant for all three sands. The value of A for temperatures between 27 F and 32 F (-2.8 C and 0 C) was found to be 0.79; hence the values of m in this temperature range can be expressed by

$$m = 0.79\, i\, (32 - T)^{0.25} \tag{4}$$

In the sands investigated, the relationship between ice content i (or water content w) and degree of ice saturation S_i can be expressed as

$$i = w = 0.917\, S_i\, n/G\, (100 - n) \tag{5}$$

where G = specific gravity of sand and n = porosity, in percent.

Thus, when the values of the adfreezing factor and uniformity coefficient are known for a given sand, then for any particular case of porosity, ice content, and temperature, the frost adfreezing stress can be calculated from the equations introduced. All idealized F versus n dotted lines representing various ice contents shown in Figures 3 to 6, and also the curves shown in Figures 7a, 7b, and 8, were obtained by using Eq. 1.

CONCLUSIONS

The ice content of a sand is one of the major factors influencing resultant frost-grip that can be exerted by that sand. The relationship is linear: For an ice content of zero percent there is no frost-grip and for an ice content greater than zero, the attendant frost-grip is directly proportional to the ice content.

The temperature of the sand-ice system has a significant influence on the magnitude of frost adfreezing. The frost-grip increases with a decrease in temperature, the rate of increase being the largest just below the freezing point. A change in temperature will produce larger changes in the frost-grip magnitude in sands having a high ice content (or degree of ice saturation) than in those having a low ice content.

Particle shape, size, and gradation also exert influence on the frost-grip. An angular particle will give higher results than a rounded particle. Under conditions of equal porosity, ice content, and temperature, uniform sand will develop higher frost-grip than well-graded sand.

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