Factors Important to the Development of Frost Heave Susceptibility Criteria for Coarse-Grained Soils

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Laboratory frost heave tests were performed to identify factors important to the development of susceptibility criteria for coarse-grained soils. The frost heave test results were evaluated by using the concept of the segregation potential. The results from 44 tests on mixtures of coarse-grained soils and a fines fraction consisting of silt and different types of clay were considered in the study. Correlations were established between heave rate and segregation potential and *(a)* percentage of particles finer than 0.074 mm, *(b)* percentage of particles finer than 0.02 mm, and *(c)* fines factor (an index property of the fines fraction that indirectly accounts for specific surface area and mineralogy of the fines fraction). The correlations are not strong for the 0.074-mm particles ($R^2 \approx 0.47$), good for the 0.02-mm particles ($R^2 \approx 0.72$), and very strong for the fines factor ($R^2 \approx 0.92$). On the basis of the results of the study, it appears that factors in addition to particle size must be considered in the development of frost heave susceptibility criteria for coarse-grained soils.

It is a matter of experience in cold regions throughout the world that the deformations or loadings resulting from frost heave can produce unacceptable levels of vertical movement and jacking of foundations, cracking in roads and airfields, and lateral movement of earth-retaining structures. Also important is the related problem of soil instability due to excess water when the segregated ice (associated with frost heave) thaws.

Three conditions are necessary for frost heave and the formation of segregated ice. First, ground temperatures must be sufficiently cold and prolonged that the soil water freezes. Second, the water table must be close to the freezing front in the soil mass so that water can migrate to a growing ice lens. Third, the soil must be susceptible to the formation of segregated ice. The basic approach to control frost heave is to eliminate one or more of these conditions. In the field, temperatures and available water cannot be easily controlled. Therefore, identifying and rejecting or removing a frost-susceptible soil is the most common approach used to control frost heave. As a consequence, the ability to identify a frost-heave-susceptible soil is of paramount importance to cold region engineers.

During the past 50 years since Taber's *(1)* treatise on the mechanism of ice segregation in soils and Casagrande's *(2)* frost heave susceptibility criteria, more than 100 different methods have been proposed to evaluate the frost heave susceptibility of soil. Obviously each new method presented has been developed because others available have proven to be unsatisfactory. Further, laboratory frost heave tests have been used extensively to create and evaluate susceptibility criteria. The lack of a suitable correlation between the results of frost heave tests and field observations is a significant factor contributing to differences in susceptibility criteria.

Disagreement between various frost heave susceptibility criteria is greatest when the susceptibility of coarse-grained soils is evaluated. Hundreds of thousands of dollars are spent each year when non-frost-heave-susceptible coarse-grained soils are rejected for use because of unduly conservative selection criteria.

In recognition of the need to identify factors that are most important to the development of frost heave susceptibility criteria for coarse-grained soils, a laboratory study was undertaken to determine the relative susceptibility of coarse-grained soils with varying gradational characteristics and fines contents. The results from the study are reported in this paper.

SEGREGATION POTENTIAL AND FROST HEAVE SUSCEPTIBILITY OF SOILS

It is universally recognized that frost heave is the result of growing ice lenses in a soil mass subjected to subfreezing temperatures. Water is drawn to the base of a growing ice lens because of a suction gradient that develops in response to the temperature gradient in the soil mass. Owing to the presence of dissolved ions, particle surface force effects, and the suction pressures that exist below the ice lens, the nucleation temperature T_s (expressed in degrees celsius) required to form ice at the base of the lens is colder than the normal freezing point of water T_i ($\approx$ 0°C), the warmest temperature at which ice can grow. The condition associated with frost heave may therefore be visualized as shown in Figure 1. At the surface there is a cold-side temperature T_c. At some depth in the soil mass, the temperature is equal to the normal freezing point of water T_i. Slightly above this depth there is a growing ice lens with a base temperature of T_s, which has been termed the segregation freezing temperature. The depth corresponding to T_i has been termed the freezing or frost front *(3)*, and the zone between the base of the ice lens and the freezing front has been termed the frost fringe *(4)*. The existence of the frozen fringe in a freezing system has been established experimentally *(5, 6)*.

In the frozen fringe liquid water exists in equilibrium with pore ice at temperatures below 0°C as adsorbed films on the surfaces of soil particles. The amount of water that can flow to the base of an ice lens is a function of the thickness of the

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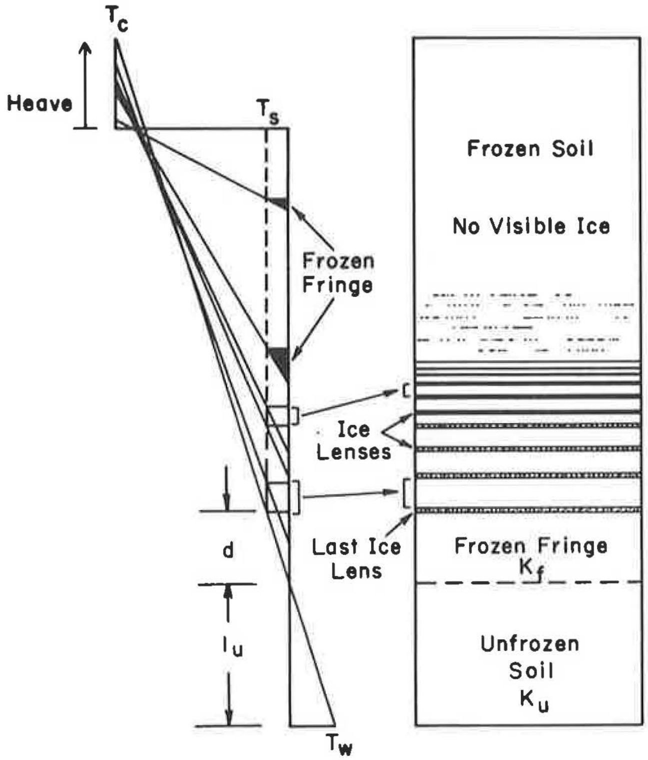

FIGURE 1 Idealization of formation of segregated ice in a soil mass [modified after Konrad and Morgenstern *(3)*].

adsorbed films, which in turn is a function of the soil particle characteristics and the temperature of the frozen fringe. Further, the amount of water that can flow to the base of the ice lens is a function of the suction gradient that exists across the frozen fringe, the suction gradient in the unfrozen soil below the frost front, and the permeability of the unfrozen soil. Indeed, frost heave may be viewed as a problem of impeded water flow to a growing ice lens *(3)*.

Under steady-state conditions, water flows to the base of the growing ice lens through the low-permeability frozen fringe and underlying unfrozen soil. The volumetric heat and latent heat, released as water is transported to the base of the ice lens and eventually forms ice, equal the heat removed when the ice lens is stationary. The frost front advances when the heat removed is greater than the latent heat released. The temperature in the frozen fringe is lowered, the permeability of the frozen fringe is reduced, and the flow of water is decreased, which in turn further reduces the latent heat released. This interrelated thermodynamic-water-flow response results in the formation of finer ice lenses near the surface of a soil column where the temperature gradient is steep and rate of heat removal is greatest. Thicker ice lenses form at greater depths in the soil column where the temperature gradient is shallow *(3)*. Also, with greater depths of frost front penetration, the thickness of the frozen fringe increases because the temperature gradient is shallower and T_s and T_i are nearly constant. The conceptual picture for the overall phenomenon is shown in Figure 1.

As the frost front slows in its advance and a near steady-state thermodynamic-water-flow condition is reached, the situation has been described mathematically by Konrad and Morgenstern *(3)* and may be summarized as follows. It is generally accepted that the Clausius-Clapeyron equation may be used to relate pressure in the liquid film at the base of a growing ice lens (u_i) to temperature; that is,

$$u_i = (L/V_w) \ln (T_{sk}/T_{ok}) = (L/V_w) \ln [1 + (T_s/T_{ok})] \qquad (1)$$

where

L = latent heat of fusion of water,
V_w = specific volume of water,
T_{ok} = freezing point of pure water (°K),
T_{sk} = segregation freezing temperature (°K).
T_s = $T_{sk} - T_{ok}$.

If it is recalled that $\ln (1 + x) = x - (1/2)x^2 + (1/3)x^3 - (1/4)x^4 + (1/n)x^n$ and second-order terms are ignored (which is reasonable for small x), Equation 1 reduces to

$$u_i = [L/(V_w \cdot T_{ok})](T_s) \qquad (2)$$

It is apparent that the first term in Equation 2 is a constant. Therefore, the suction that develops at the base of a growing ice lens, under near steady-state conditions (i.e., very slow frost penetration rate), is a function of a soil property only, namely, the segregation freezing temperature.

Now consider the two-layer system consisting of the frozen fringe and unfrozen soil beneath the last ice lens. Assuming that *(a)* there is no accumulation of water in the frozen fringe, *(b)* Darcy's law is valid for the flow regime that exists, and *(c)* the permeabilities in the frozen fringe and unfrozen soil are constant, then (by applying Darcy's law)

$$v = \Delta H/[(d/K_f) + (l_u/K_u)] \qquad (3)$$

where

v = velocity of water flow to ice lens,
ΔH = total head loss between base of ice lens and base of soil column,
l_u = thickness of unfrozen soil,
d = thickness of frozen fringe,
K_u = permeability of unfrozen soil, and
K_f = permeability of frozen fringe.

l_u and d may be evaluated for a given temperature gradient, warm side temperature T_w, and a soil with a specific value of T_s.

The total head loss may be expressed in terms of the results obtained from the Clausius-Clapeyron equation; that is,

$$\Delta H = u_i + h_{ei} - u_b - h_{eb}$$

$$\Delta H = (1/\gamma_w) [L/(V_w \cdot T_{ok})] (T_s) + h_{ei} - u_b - h_{eb} \qquad (4)$$

where h_{ei} and h_{eb} are elevation heads at the base of the last ice lens and soil column, respectively, and u_b is porewater pressure at the base of the soil column. Taking the base of the soil column at the water level, $u_b = 0$. Further, for a saturated soil column with the water level close to the last ice lens, $h_{ei} \approx h_{eb}$. Thus Equation 4 reduces to

$$\Delta H = [L/(\gamma_w \cdot V_w \cdot T_{ok})]\ (T_s) \quad (5)$$

By combining Equations 3 and 5, it is apparent that the velocity of water flow to the base of a growing ice lens for a given temperature gradient is a function of soil properties only, that is, K_u, K_f, and T_s. Consequently, the rate of heave, 1.09 times the velocity of water flow, is also a function of soil properties only for a given temperature gradient.

Next consider two columns of identical soil freezing under different temperature gradients as shown in Figure 2. From Equation 5 it may be noted that the total head loss from the base of the last ice lens and soil column (ΔH) is the same for both cases. Further, the average temperature in the frozen fringe is the same for both columns, suggesting that the average unfrozen water content is the same. This implies that the average permeability (K_f) is the same in both cases. The permeability of the unfrozen soil (K_u) may also be assumed to be equal in both cases.

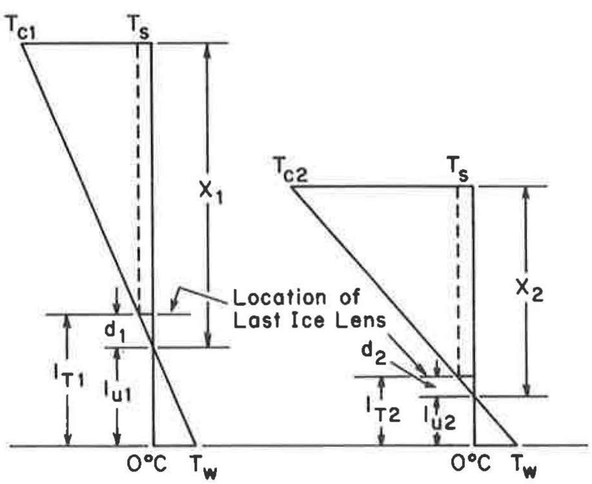

FIGURE 2 Formation of segregated ice under two different temperature gradients [after Konrad and Morgenstern *(3)*].

As a consequence of these identities and assumptions, the flow velocities for the two cases may be written as

$$v_1 = \Delta H/[(d_1/K_f) + (l_{u1}/K_u)]$$

$$v_2 = \Delta H/[(d_2/K_f) + (l_{u2}/K_u)] \quad (6)$$

Note that subscripts for ΔH, K_f, and K_v have been omitted, because they are equivalent for both cases.

By noting similar triangles under the two different freezing conditions,

$$T_s/d_1 = T_w/l_{u1} \quad T_s/d_2 = T_w/l_{u2} \quad (7)$$

$$T_s/T_w = d_1/l_{u1} = d_2/l_{u2} \quad (8)$$

If the ratio of velocities is taken,

$$v_1/v_2 = [(K_u \cdot d_2) + (l_{u2} \cdot K_f)]/[(K_u \cdot d_1) + (l_{u1} \cdot K_f)] \quad (9)$$

From Equation 8

$$l_{u2} = (d_2 \cdot l_{u1})/d_1 \quad (10)$$

Substituting Equation 10 into Equation 9 and factoring out d_1 and d_2,

$$v_1/v_2 = (d_2/d_1)[K_v + (l_{u1}/d_1) \cdot K_f]/[K_v + (l_{u1}/d_1) \cdot K_f]$$
$$= d_2/d_1 \quad (11)$$

and

$$v_1 d_1 = v_2 d_2 \quad (12)$$

But

$$d_1 = T_s/\text{grad } T_1 \qquad d_2 = T_s/\text{grad } T_2 \quad (13)$$

in which grad T is the temperature gradient below the base of the ice lens. Substituting Equations (13) into Equation (12),

$$v_1/\text{grad } T_1 = v_2/\text{grad } T_2 = \text{constant} \quad (14)$$

Now the significance of Equation 14 is that if the ratio of the intake velocity and temperature gradient is a constant, it may be established from the results of tests conducted at any temperature gradient. Further, if the ratio of flow velocity to temperature gradient is known for a particular soil, the intake velocity (and hence heave rate) may be established for another temperature gradient by simple multiplication.

Konrad and Morgenstern *(3)* have termed the ratio of water intake velocity to temperature gradient the segregation potential *(SP)*. They have shown that the segregation potential is

$$SP = V/\text{grad } T = (\{[L/(\gamma_w \cdot V_w \cdot T_{ok})](T_s) - u_0\}/T_s)K_f \quad (15)$$

where u_0 is the suction at the base of the frozen fringe (which is close to the 0°C isotherm). The segregation potential, once evaluated at near steady-state conditions, and under the conditions previously noted (i.e., a saturated soil column with negligible overburden pressure), may be considered an index property of a soil that uniquely identifies the frost heave susceptibility considering the assumptions noted earlier. The greater the segregation potential, the greater the heave in a soil mass in response to a given set of freezing conditions.

To relate the segregation potential of a soil to field conditions, one must consider the influence of *(a)* suction at the frost front (associated with the depth to the groundwater table), *(b)* pressure applied to the warmest ice lens (associated with the weight of the soil column and surcharge loads above the lens), and *(c)* rate of cooling of the frozen fringe (associated with frost penetration rates and average temperature gradients in the frozen zone). In a series of papers, Konrad and Morgenstern *(7–11)* discussed the significance of these variables and extended the concept of the segregation potential to address frost heave prediction under field conditions. They demonstrated that only a limited number of freezing tests are required to fully characterize the segregation potential of a soil for most field problems.

DESCRIPTION OF TEST SYSTEM

The segregation potential may be evaluated in the laboratory in a frost heave test by freezing a soil specimen and noting the intake of water into the specimen and the temperature along the specimen. Although it is desirable to apply the results of this and other laboratory investigations to actual field situations, only relative frost heave susceptibilities, as measured in the laboratory, were determined. The frost heave tests were performed under worst-case conditions to minimize the influence of variables other than gradational characteristics of the materials and the fines content. To achieve conditions that were most conducive to frost heaving, the specimen was saturated and the free water surface was maintained at approximately the same level as the frost front. No surcharge was applied to the specimen.

The frost heave cell employed in the study is shown in Figure 3. The cell, sample preparation, test procedure, and interpretation of the test results have been described in detail by Mageau and Sherman *(12)* amd Rieke *(13)*. The frost heave cell consists of a nylon barrel 30.5 cm (12.0 in.) long by 10.2 cm (4.0 in.) I.D. by 15.2 cm (6.0 in.) O.D. The specimen is placed inside the cell and an aluminum top cap and bottom plate serve as constant-temperature boundaries. The temperatures of the top cap and bottom plate are maintained at constant values by circulating constant-temperature fluids through heat exchange mazes within the cap and plate. To aid in the boundary temperature control and to prevent radial heat flow, the cell was placed in a refrigerator whose temperature was maintained at approximately 2°C. A 50-mL buret was connected to the water intake line and the flow of water into or out of the specimen during a test was noted by the change in the water level in the buret. The change in the height of the specimen during the test (reflecting frost heave) was measured with a linear variable differential transformer (LVDT). The temperature along the length of the specimen was monitored with thermistors adjacent to the soil embedded in the wall of the nylon cell barrel. Before freezing, the specimen was consolidated one-dimensionally under 50 kPa (7 psi) pressure and allowed to reach thermal equilibrium with the ambient refrigerator temperature.

The segregation potential was calculated for each frost heave test by using the measured intake of water and the temperature along the specimen as noted by the thermistors at near steady-state conditions. Near steady-state conditions usually occurred 13 to 14 hr after the test had been initiated. The temperature gradient at the end of the test was also determined and the average of the two (i.e., at 13 to 14 hr and at end of the test) was used in the calculations. The segregation potential has been shown to be independent of the temperature gradient at near steady-state conditions (see Equation 14). However, all samples were subjected to the same top-cap and bottom-plate temperatures. The heave rate for each sample at near steady-state conditions was also determined.

LABORATORY TEST PROGRAM AND MATERIALS

The soils used in the laboratory test program were mixtures of pea gravel or well-graded coarse sand with 2, 4, 5, 8, and 20 percent fines (i.e., diameter less than 0.074 mm). For the majority of the tests, the fines consisted of a mixture of 75 percent silt and 25 percent poorly crystallized kaolinite. Several tests were also conducted by mixing Hanover silt (with the plus 0.074-mm particles removed) with well-crystallized kaolinite. Grain size distributions for both types of coarse material and Hanover silt are shown in Figure 4. Specific

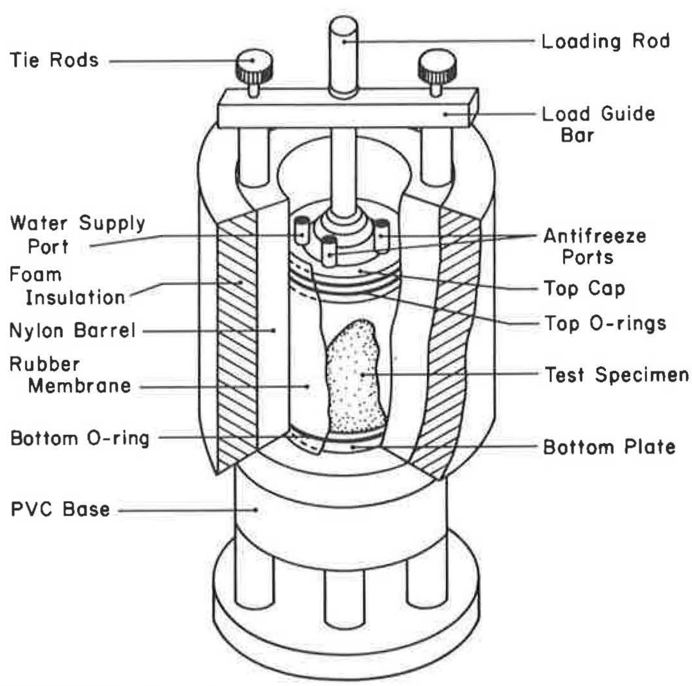

FIGURE 3 Frost heave test cell.

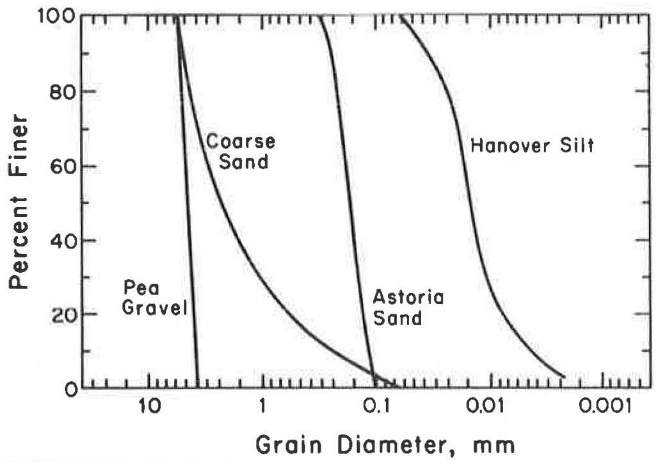

FIGURE 4 Grain size distributions for soil employed in test program.

gravity values are given in Table 1. Because it was desirable to control the effects of different clay minerals, clays with greater than 90 percent purity were required. To this end clays available from the Clay Minerals Society of America (Columbia, Missouri) were used. The diameter of the clay particles was assumed to be less than 0.002 mm.

The different components of pea gravel, sand, silt, and clay used in the soil sample mixture were weighed to ±0.5 g. Because a 2000-g sample was typically used, the resulting accuracy of the component percentages was ±0.025 percent. The components were thoroughly mixed in order to obtain a homogeneous sample. The void ratios of the samples used for the frost heave susceptibility tests ranged from 0.44 to 0.68 (porosities from 0.30 to 0.41). The void ratio was obtained by using a weighted average of the specific gravities of the soil components.

Thirteen frost heave tests were performed on various combinations of sand, pea gravel, silt, and clay. In seven of the tests, the material retained on the No. 200 sieve (0.074 mm) consisted of well-graded coarse-grained sand whereas the fines fraction consisted of mixtures of silt and different types of clay. In six tests, the material retained on the No. 200 sieve consisted of uniform pea gravel. A summary of the combinations of mixtures used in the study is given in Table 2. The percentage of material smaller than 0.02 mm, the uniformity coefficient, and the coefficient of curvature for each sample are also presented. The data base developed in the present study may be supplemented with the results from 31 tests presented by Rieke et al. *(14)* for soil mixtures consisting of a fine sand from Astoria, Oregon, and various percentages of fine soil materials previously discussed. The grain size distribution for Astoria sand is shown in Figure 4 and the specific gravity is given in Table 1.

TABLE 1 SPECIFIC GRAVITIES OF SOILS USED IN TEST PROGRAM

Soil	Clay Mineral Society Symbol	Specific Gravity
Well-graded coarse-grained sand	–	2.65
Pea gravel	–	2.68
Kaolinite		
Well crystallized	KG_a-1	2.60
Poorly crystallized	KG_a-2	2.60
Hanover silt	–	2.69
Astoria sand	–	2.75

TEST RESULTS

The purpose of this study was to identify factors important to the frost heave susceptibility of coarse-grained soils. The fines content (the percentage of particles smaller than 0.074 mm) has been identified by many researchers as an important factor. Indeed, the majority of the classification systems employed in the United States to assess frost heave susceptibility of soils are based on a percentage of material finer than 0.074 mm *(15)*. Casagrande *(2)*, however, identified the 0.02-mm fraction as being particularly important to the formation of segregated ice in a soil and stated:

TABLE 2 PERCENTAGE OF SOIL MIXTURE COMPONENTS, COEFFICIENT OF UNIFORMITY, AND COEFFICIENT OF CURVATURE OF TEST SAMPLES

Test No.	Coarse Material		Silt (%)	Clay		Percent Finer Than 0.074 mm	Percent Finer Than 0.02 mm	C_u	C_c	Segregation Potential (mm^2/°C-day)	Heave Rate (mm/day)
	Percent	Type		Percent	Type						
1	100	Well-graded sand	–	–	–	–	–	11	1.1	0.0	0.0
2	98	Well-graded sand	1.5	0.5	PCK	2	1.3	15	1.7	0.0	0.0
3	96	Well-graded sand	3.0	1.0	PCK	4	2.5	16	1.8	0.0	0.9
4	92	Well-graded sand	6.0	2.0	PCK	8	5.0	19	1.9	73	2.3
5	80	Well-graded sand	15.0	5.0	PCK	20	12.5	150	5	147	5.0
6	80	Well-graded sand	10.0	10.0	PCK	20	15.0	1350	46	232	7.8
7	95	Well-graded sand	1.0	4.0	WCK	5	4.5	17	1.8	86	3.2
8	92	Pea gravel	6.0	2.0	PCK	8	5.0	1.2	0.9	76	2.5
9	80	Pea gravel	15.0	5.0	PCK	20	12.5	370	323	203	6.7
10	80	Pea gravel	10.0	10.0	PCK	20	15.0	2900	2421	300	12.7
11	95	Pea gravel	1.0	4.0	WCK	5	4.5	1.1	0.9	67	2.5
12	91	Pea gravel	1.8	7.2	PCK	9	8.1	1.1	0.9	90	4.6
13	96	Pea gravel	3.0	1.0	PCK	4	2.5	1.1	0.9	0.0	0.8

Note: PCK = poorly crystallized kaolinite; WCK = well-crystallized kaolinite; $C_u = D_{60}/D_{10}$; $C_c = D_{30}^2/(D_{60} \times D_{10})$.

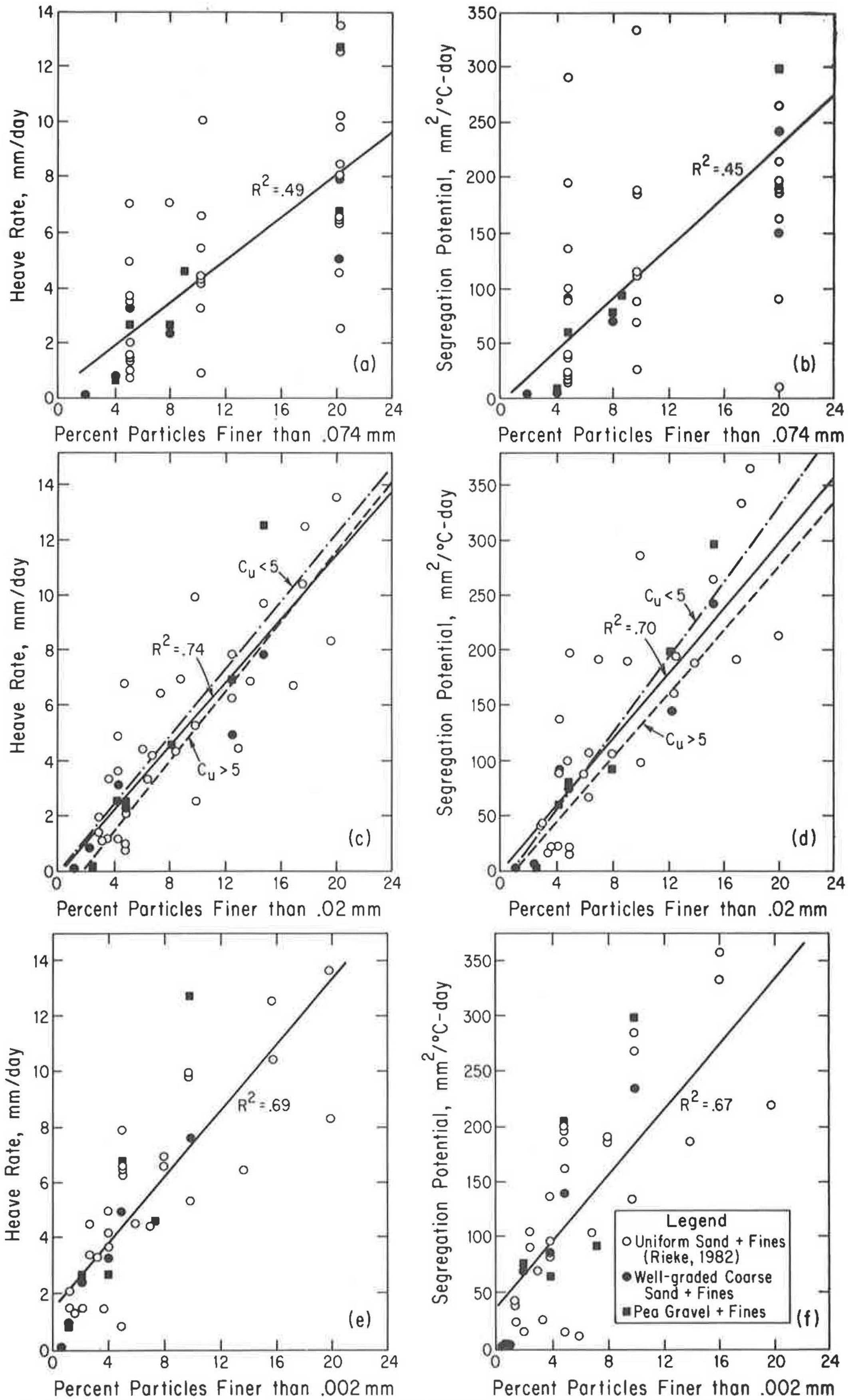

FIGURE 5 Heave rate and segregation potential versus percentage of particles finer than 0.074, 0.02, and 0.002 mm.

Under natural freezing conditions and with sufficient water supply one should expect considerable ice segregation in nonuniform soils containing more than 3% of grains smaller than 0.02 mm, and in very uniform soils containing more than 10% smaller than 0.02 mm. No ice segregation was observed in soils containing less than 1% of grains smaller than 0.02 mm, even if the ground water was as high as the frost line.

The results of the present study in terms of the heave rate and segregation potential versus the percentage of particles finer than 0.074 and 0.02 mm are presented in Figure 5. It is clear that the correlation between heave rate or segregation potential and the percentage of particles finer than 0.074 mm (see Figure 5*a* and *b*) is not strong. At a given percent finer than 0.074-mm, the heave rate or segregation potential varies by over a factor greater than 10. The poor correlation and great range in frost heave response suggest that the continued use of the 0.074-mm grain size alone as an indicator of frost heave susceptibility is not justified.

The correlation between heave rate and segregation potential and the percentage of particles finer than 0.02 mm (see Figure 5*c* amd *d*) is good. It would appear that if one is to base a classification system on particle size alone, the 0.02-mm size is an excellent choice. Further, the correlation between frost heave response and particle size is not improved if the clay size fraction (0.002 mm) is used (see Figure 5*e* and *f*). In fact, the correlation between heave rate or segregation potential and percentage of particles finer than 0.002 mm is not as strong as the correlation for 0.02 mm (but the difference in R^2-values is not great).

The uniformity of a soil is often expressed in terms of the coefficient of uniformity (C_u). If C_u is greater than approximately 5, the soil is well-graded; if the coefficient of uniformity is less than 5, the soil is uniform. The coefficients of uniformity were calculated for the soil mixtures employed in the study and the mixtures were divided into well-graded soils ($C_u > 5$) and uniform soils ($C_u < 5$). The correlation between heave rate and segregation potential and percentage of particles finer than 0.02 mm is shown in Figure 5*c* and *d*. The difference between the correlations associated with $C_u > 5$, $C_u < 5$, and the combined data set is not great.

Lambe et al. *(16)* found that the mineralogy of the clay in the fines fraction influenced the frost heave susceptibility of soils. Specifically, clays with high activities could actually decrease frost heave when added to frost-susceptible materials.

On the basis of more than 30 frost heave tests conducted on 11 distinct soil mixtures, Rieke et al. *(14)* found that the segregation potential of a soil increased with increasing percentage of fines, decreasing activity of the fines fraction, and for a specific fines fraction mineralogy, increasing liquid limit of the fines fraction. They developed a term based on empirical observations that had a strong correlation with the segregation potential of a soil, namely,

$$R_f = [(\text{percentage of fines})(\text{percentage of clay sizes in fines fraction})]/(\text{liquid limit of fines fraction})$$

where R_f is the fines factor, percentage of fines is material passing the No. 200 (0.074-mm) sieve, percentage of clay sizes is material smaller than 0.002 mm, and liquid limit (LL_f) is liquid limit of material passing the No. 200 (0.074 mm) sieve. The fines factor may be viewed as an index property of the fines fraction that indirectly accounts for the specific surface area and mineralogy of the fines fraction.

On the basis of the analysis of the fines factor, it may be demonstrated that the permeability of the frozen fringe, and hence a soil's tendency to heave, is a function of not only specific surface area but also the mineralogy of the fines fraction. It is hypothesized that fines fractions with highly active clay minerals have less mobile unfrozen water films in the frozen fringe, which results in a reduced frozen fringe permeability.

The heave rate and segregation potential versus fines factor for the soil mixtures considered in the study is shown in Figure 6. The correlation coefficients are high. Consequently, it may be concluded that factors other than particle size alone must be

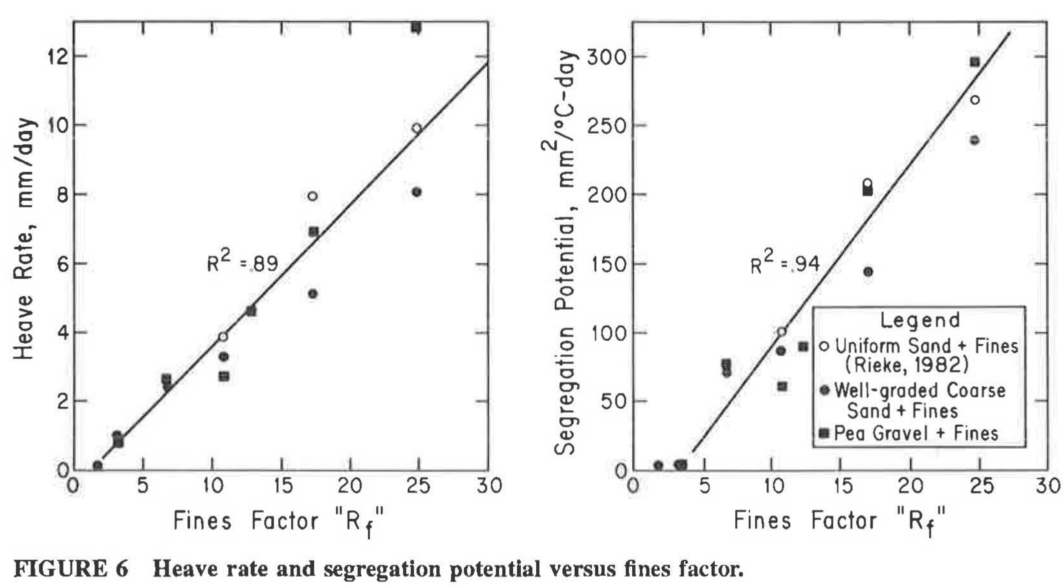

FIGURE 6 Heave rate and segregation potential versus fines factor.

considered in the development of frost heave susceptibility criteria for coarse-grained soils.

SUMMARY AND CONCLUSIONS

On the basis of the results of 44 frost heave susceptibility tests conducted on coarse-grained soils with varying percentages and mineralogy of the fines fraction, the following conclusions may be drawn:

1. The correlation between heave rate or segregation potential and the percentage of particles finer than 0.074 mm is not strong; the continued use of the 0.074-mm grain size alone as an indicator of frost heave susceptibility is not justified.
2. The correlation between heave rate or segregation potential and the percentage of particles finer than 0.02 mm is good; the difference between the correlations for the 0.02-mm particle associated with well-graded soils and those for uniform soils is not great.
3. The correlation between heave rate or segregation potential and the fines factor (a term that considers the percentage of fines and mineralogy of the fines fraction) is the strongest of those considered in the present study. It suggests that factors in addition to particle size must be considered in the development of frost heave susceptibility criteria for coarse-grained soils.

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