Molding Water Content and Hydraulic Conductivity of Compacted Soils Subjected to Freeze/Thaw

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Independent researchers have shown that when compacted clays are subjected to freeze/thaw, they can undergo increases in hydraulic conductivity of one to three orders of magnitude. Existing data have shown that these changes are highly dependent on the initial (before freezing) hydraulic conductivity but not on the plasticity of the soil. The number of freeze/thaw cycles, state of stress, and rate of freezing have the greatest effect on the hydraulic conductivity. It has also been indicated that the availability of water during freezing is critical. In this study, it is shown for closed systems (those with no external water source) that the severity of damage to the soil during freeze/thaw correlates with the volume of water contained in the soil pores and with changes in the hydraulic conductivity. Soils compacted dry of optimum water content can be expected to undergo less than one order of magnitude change in hydraulic conductivity because of freeze/thaw, whereas those compacted wet of optimum can be expected to change by two or more orders. This difference in the magnitude of change suggests that to maintain hydraulic conductivities in compacted soils subjected to freeze/thaw, it may be necessary to compact them dry of optimum—a condition contrary to the practice of constructing low hydraulic conductivity barriers.

Compaction of fine-grained soils can yield materials having low hydraulic conductivities, which are typically utilized in seepage containment applications (*1–3*). In some applications, such as pavement subgrades, landfill liners and covers, and waterproofing for subsurface structures, the soil may be exposed to freeze/thaw conditions. It has been shown that compacted soils subjected to these conditions can undergo changes resulting in order-of-magnitude increases in the hydraulic conductivity of the soil (*4–9*). The conditions of the soil during freeze/thaw promote such changes, which are addressed in this paper.

Factors that significantly affect the resulting hydraulic conductivity include the rate of freezing, number of freeze/thaw cycles, and status of stress on the soil. Secondary factors include the ultimate or minimum temperature of the frozen specimen, the dimensionality of freezing (three-dimensional versus one-dimensional), and the availability of water. These factors have been studied by several investigators and documented in a state-of-the-art paper by Othman and Benson (*5*). It is not the intent to evaluate each of them again. Rather, a second analysis of the available data affords opportunity to highlight factors that appear to be controlling the changes in the hydraulic conductivity of the soils.

Analysis of the data in light of the factors that might correlate with the changes in hydraulic conductivity was performed. The water available within the soil during the time of freeze/thaw was the main parameter studied. Since all the specimens were tested in a closed system, the only water available during freezing was that contained within the soil pores.

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BACKGROUND

Numerous investigators have shown that freeze/thaw conditions can have deleterious effect on the hydraulic conductivity of compacted soils (*4–9*). Data shown in Figure 1 exhibit increases in hydraulic conductivities of up to three orders of magnitude. It is hypothesized that a process by which the pore size or effective porosity is increasing is occurring in the soil, since the largest pores in a fine-grained soil govern the hydraulic flow through that medium (*10*).

Hunsicker (*11*) used scanning electron microscopy (SEM) to delineate small cracks (0.005 mm) in the microstructure of thawed soil. Chamberlain et al. (*12*) used thin-section analysis to photograph macroscale cracking patterns in soils that had undergone freeze/thaw. Kim and Daniel (*6*) used tracer studies to compare effective porosities (volume of fluid-conducting pores divided by the total volume of the soil) of specimens having undergone freeze/thaw and those for control specimens. They found that effective porosities of freeze/thaw specimens (compacted slightly wet of optimum) increased from 10 to 80 percent above those of the unfrozen specimens (*6*). In each of these investigations, it was the porosity or effective porosity that was altered in the soil specimens, indicating that a change in hydraulic conductivity could be anticipated.

The increase in effective porosity (referred to here as "damage") results from several phenomena, some or all of which may occur for a given specimen. The first simply involves expansion of the water (about 9 percent by volume) in the pores as it turns to ice. The second phenomenon is the growth of segregated ice as water migrates to the freezing zone and increases the volume and size of an ice lens within the soil. The final phenomenon is the potential shrinkage of soil, specifically the clay fraction, as water migrates from the soil and joins the growing ice lens. Taken in sum, these processes result in increasing the sizes and interconnectedness of the pores in the subsequently thawed soil. The result can be a soil with a hydraulic conductivity much greater than that before it underwent freezing. In summary, a factor in predicting the degree of damage that may occur to soils is knowledge of the water availability during freeze/thaw.

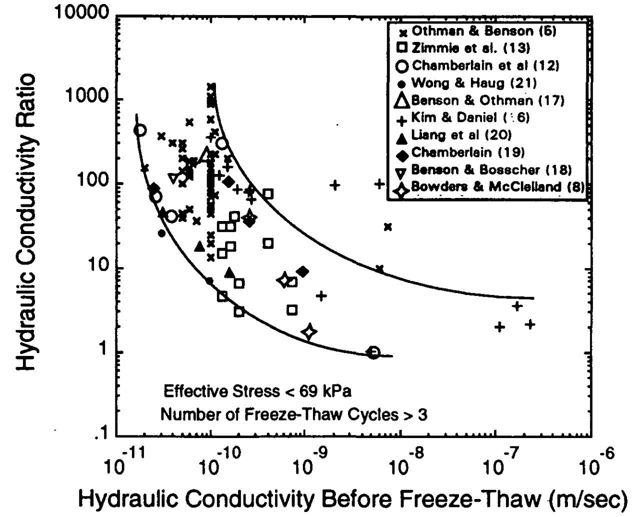

FIGURE 1 Hydraulic conductivity ratio versus hydraulic conductivity before freeze/thaw (*7*).

DATA

Data from three sources (*6–8*) have been compiled and analyzed. A total of six soils are included. The geotechnical and index properties of the soils are provided in Table 1. The soils represented cover a range in material properties expected of seepage containment applications. The data represented in this analysis include only those in which standard Proctor energy was used. Four specimens were subjected to one-dimensional freezing. All of the others were subjected to three-dimensional freezing.

The data included in this study are provided in Tables 2 through 4. The dry densities (γ_{dmax}) and water contents are those of the specimen during specimen molding. The delta water content ($\Delta w\%$) yis the difference between the molding water content and the optimum water content (w_{opt}). K_{ratio} is the ratio of the hydraulic conductivity after a specimen has been subjected to freeze/thaw to the hydraulic conductivity of the specimen (or a similar one) before it has been subjected to freeze/thaw. Only specimens subjected to five or more freeze/thaw cycles are included in the data set. It has previously been shown that the most significant damage occurs within the first five freeze/thaw cycles (*5,12,13*). In addition, the relative magnitude of the effective stress on the specimen during the time that the hydraulic conductivity was measured is reported for each hydraulic conductivity ratio. The significance of the applied effective stress on the measured hydraulic conductivity has been demonstrated previously (*7,8,14*).

TABLE 1 Geotechnical and Index Properties of Soils Subjected to Freeze/Thaw and Permeated

			Soil No. and Type of Soil[a]							
			1 and 2, Kaol	3, Wetzel	4, Mon	5, Wisconsin A	6, Wisconsin B	7, Wisconsin C	8, Wisconsin A	Range
γ_{dmax}	(kN/m³)		13.5	19.1	15.2	18.0	16.8	14.7	18.2	13.5–19.1
w_{opt}	(%)		31	11	23	16	18.5	26	15	11.0–31.0
P_{200}	(%)		90	50	65	85	99	71	88	50.0–99.0
LL	(%)		58	33	60	34	42	84	36	33.0–84.0
PI	(%)		24	9	30	16	19	60	19	9.0–60.0
e		at γ_{dmax} and w_{opt}	0.88	0.38	0.72	0.54	0.53	0.81	—	0.38–0.88
n	(%)	at γ_{dmax} and w_{opt}	47	28	42	35	35	45	—	28.0–47.0
S_R	(%)	at γ_{dmax} and w_{opt}	91	78	86	82	95	87	—	78.0–95.0

NOTE: γ_{dmax} = maximum dry density; w_{opt} = gravimetric water content at γ_{dmax}; P_{200} = percent passing No. 200 sieve; LL = liquid limit; PI = plasticity index; e = void ratio; n = porosity; S_R = degree of saturation.

[a]Investigators: Soil Nos. 1–4, Bowders and McClelland (*8*); Nos. 5–7, Othman et al. (*7*); No. 8, Kim and Daniel (*6*).

TABLE 2 Molding Conditions, Effective Stress, Pre-Freeze/Thaw Hydraulic Conductivity, and K_{ratio} for Soil Specimens (*8*)

Soil and Soil No.	γ_d (kN/m³)	$w\%$	Δw	$K_{initial} \times 10^{-8}$ (cm/sec)	K_{ratio} σ (kPa) ≤25	25–42	63–70	115–210
Kaol, 1	13.5	32.5	1.5	5 to 8	4.6	1.6	2.4	1.2
Kaol, 2	13.5	32.5	1.5	4 to 8	43	—	1.4	1.0
Wetzel, 3	19.1	12.5	1.5	9 to 10	1.8	2.1	—	1.2
Mon, 4	15.2	24.5	1.5	1.0	49	23	15	7.4

NOTE: Data for each soil in this table represent the average values of four specimens tested under these conditions. Soil No. refers to soils listed in Table 1. γ_d = dry density (kN/m³); $w\%$ = molding water content (%); Δw = difference between molding and optimum water contents; σ = effective stress in soil during permeability test (kPa); K_{ratio} = hydraulic conductivity ratio (i.e., hydraulic conductivity post-freeze/thaw divided by that prior to freeze/thaw).

TABLE 3 Molding Conditions, Effective Stress, Pre-Freeze/Thaw Hydraulic Conductivity, and K_{ratio} for Soil Specimens (*7*)

Soil No. and Spec. No.	γ_d (kN/m^3)	w%	Δw	$K_{initial}$ (cm/sec)	K_{ratio} σ (kPa) ≤25	25–42	63–70	115–210
Othman Soil A, 5								
PV 55/51	18.0	15.9	−0.1	2.7E-7	3.7			
50/49	18.3	16.1	0.0	4.0E-8	22			
34/7	18.2	16.9	0.9	1.1E-8	418			
40/7	18.2	17.4	1.4	1.1E-8	73			
44/11	17.6	18.8	2.8	1.1E-8	73			
66/23	17.4	19.8	3.8	1.1E-8	109			
67/23	17.5	19.8	3.8	1.1E-8	64			
18/20	17.1	20.2	4.2	1.5E-8	200			
22/20	17.0	20.5	4.5	1.5E-8	167			
Othman Soil B, 6								
VT 13/10	17.3	17.0	−1.5	7.5E-7	56			
45/43	17.4	19.2	0.7	4.2E-8	13			
7/8	17.4	19.9	1.4	1.0E-8	130	—	37[a]	2.2[b]
26/28	16.5	22.4	3.9	1.0E-8	150			
Othman Soil C, 7								
SC 9/8	14.8	25.7	−0.3	6.0E-7	10			
42/4	14.9	28.4	2.4	2.5E-8	8.8			
45/4	14.2	28.4	2.4	2.5E-8	52			
103/101	14.7	30.3	4.3	6.0E-9	600			

NOTE: Soil No. refers to soils listed in Table 1. Spec. No. (PV#, VT#, and SC#) is the test specimen number. γ_d = dry density (kN/m^3); w% = molding water content (%); Δw = difference between molding and optimum water contents; σ = effective stress in soil during permeability test (kPa); K_{ratio} = hydraulic conductivity ratio (i.e., hydraulic conductivity post-freeze/thaw divided by that prior to freeze/thaw).
[a]K pre-freeze was 7.0E-9 cm/sec.
[b]K pre-freeze was 5.0E-9 cm/sec.

ANALYSES AND DISCUSSION

The data examined in this analysis were tested under closed-system conditions during freeze/thaw. Under such conditions, there is no source of water during freezing except for that already contained in the soil pores. Thus, any ice lenses that might form are limited in size to the volume of pore water available in the specimen. On the basis of this condition, the hypothesis here is that the severity of damage to the soil is directly related to the volume of water contained in the soil pores. Thus, it follows that changes in the hydraulic conductivity should also directly relate to the volume of water in the soil.

The hydraulic conductivity ratios versus molding water content for the six soils are shown in Figure 2. The relative effective stress on the specimens is indicated. Although there is scatter in the data, there is evidence that increased effective stress on the soil results in less damage or increase in hydraulic conductivities due to the action of freeze-thaw.

The data by Kim and Daniel (*6*) showed two orders of magnitude difference in hydraulic conductivity ratio for soils compacted wet of optimum compared with those compacted dry of optimum water content. Thus, merely recording the molding water content does not provide enough information about the availability of water in the specimens. For instance, if a specimen is compacted at 15 percent water content but the optimum water content is 20 percent, the soil will be well dry of optimum and soil pores will contain a larger percentage of air than when compacted wet of optimum. Given a closed system for freezing, it is likely that the soil that is dry of optimum will sustain less relative freeze/thaw damage.

Shown in Figure 3 is the hydraulic conductivity ratio versus the difference between the molding and optimum water contents.

TABLE 4 Molding Conditions, Effective Stress, Pre-Freeze/Thaw Hydraulic Conductivity, and K_{ratio} for Soil Specimens (*6*)

Soil No. and Spec. No.	γ_d (kN/m^3)	w%	Δw	$K_{initial}$ (cm/sec)	K_{ratio} σ (kPa) ≤25
Soil No. 8					
1	17.6	11	−4.1	1.1E-5	2
2	18.2	13.2	−1.9	1.7E-5	3.5
3	18.6	15.1	0.0	2.1E-7	95
4	18.4	16.4	1.4	1.5E-8	160
5	17.6	19.5	4.4	1.2E-8	125
6	16.5	22.1	7.0	2.6E-8	85

NOTE: Soil No. refers to soils listed in Table 1. Spec. No. is the test specimen number. γ_d = dry density (kN/m^3); w% = molding water content (%); Δw = difference between molding and optimum water contents; σ = effective stress in soil during permeability test (kPa); K_{ratio} = hydraulic conductivity ratio (i.e., hydraulic conductivity post-freeze/thaw divided by that prior to freeze/thaw).

Only data for low effective stress (<25 kPa) are displayed. Although degree of saturation (ratio of volume of water in the soil pores to total volume of pores) would have been a good measure to use, the authors had insufficient information to make this determination for all of the data; however, knowing the molding water content relative to the optimum water content for the soil provides an indication of the relative degree of saturation of the soil (*15*). Data points lying to the left of the zero on the horizontal axis indicate soils compacted dry of optimum. Degrees of saturation are low. The soils contain significant quantities of air in their pores; therefore, less water is available for the formation of ice when the soils are subjected to freezing temperatures. For soils lying to the left of zero, one expects less damage and smaller hydraulic conductivity ratios. Points lying to the right of the null value are soils compacted wet of optimum. As soils become increasingly wet of optimum, they obtain higher degrees of saturation and in a closed system, more water is available for ice formation. Thus, one would expect more damage or increased magnitude of the hydraulic conductivity ratios. Indeed, the data shown in Figure 3 indicate such a behavior.

A linear regression including the data for all six soils, at effective stresses below 25 kPa, is shown in Figure 4. Molding water contents for the specimens shown span from approximately 4 percent dry of optimum to 7 percent wet of optimum. For soils well dry of optimum, it is clearly evident that for soils dry of optimum, the hydraulic conductivity ratio decreases rapidly as one moves away from the optimum water content. Also evident is the increasing hydraulic conductivity ratio as soils become increasingly wet of optimum. There are two data points, K_{ratio} 418 and 600, that shift the linear regression curve. Although the integrity of these points is not in question, they have been deleted from the analysis for the sake of examining the resulting regression curve as shown in Figure 5. The curve shifts down but does not appreciably change slope.

The data shown in Figures 4 and 5 support the hypothesis that increased water availability during freezing results in increased damage to the soil and higher hydraulic conductivity ratios. Othman at al. (*7*) found that hydraulic conductivity ratios increased as the hydraulic conductivity of the unfrozen soil decreased. Typically, hydraulic conductivity of a cohesive soil can be decreased by compacting it at a water content wet of optimum. This is a

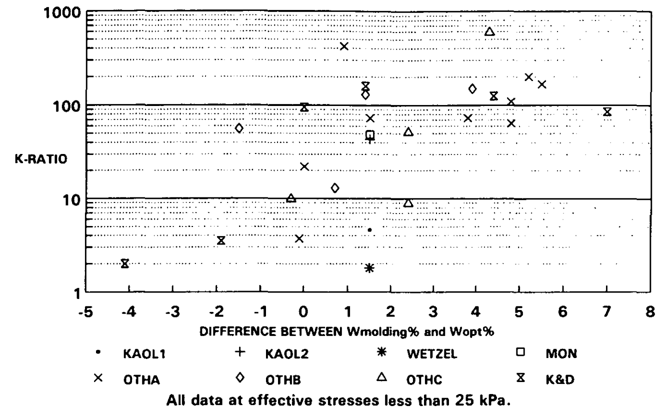

FIGURE 3 ***K*-ratio versus *w*% deviation from w_{opt}%: data.**

common practice and often specified for soils being used in containment applications (*3*). When soils are compacted wet of optimum and subjected to several cycles of freeze-thaw, the resulting hydraulic conductivity of the thawed soil is likely to be increased above that of the unfrozen soil.

A point that must not be ignored is illustrated in Figure 6. This is the impact of effective stress on the final hydraulic conductivity of soil subjected to freezing and thawing. As the effective stress in the soil is increased, the hydraulic conductivity ratio (or final hydraulic conductivity) is decreased. In fact, for stresses greater than about 70 kPa (10 psi) the damage due to freeze/thaw action may be completely nullified. This behavior is in agreement with that reported by LaPlante and Zimmie (*4*) for soils subjected to freeze/thaw and by Boynton and Daniel (*14*) for soils subjected to damage by desiccation cracking.

CONCLUSIONS

Data on the hydraulic conductivity of compacted soils having undergone freeze/thaw exposure have been compiled and analyzed. Six different soils were examined. The findings, in agreement with those of previous investigators, are as follows:

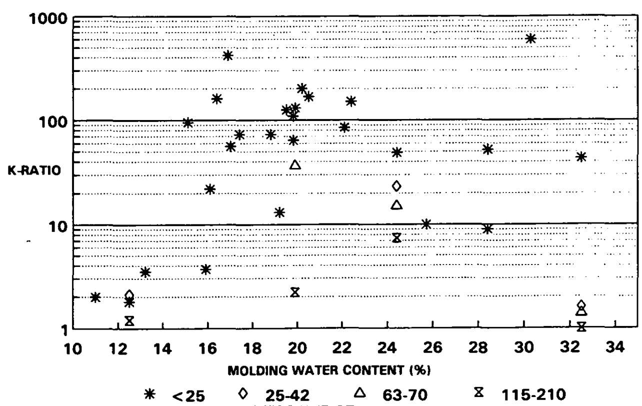

FIGURE 2 ***K*-ratio at various effective stresses versus molding water content.**

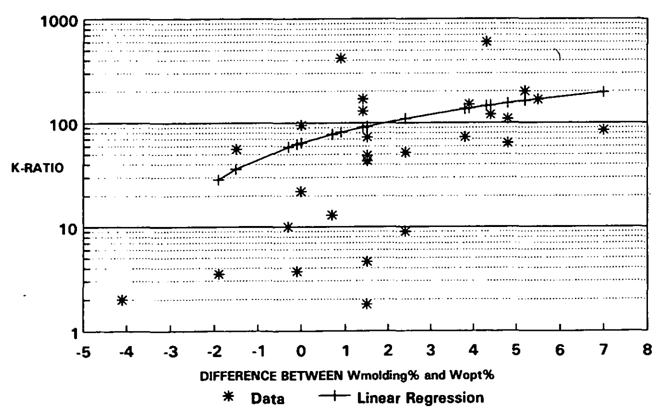

FIGURE 4 ***K*-ratio versus *w*% deviation from w_{opt}%: linear regression.**

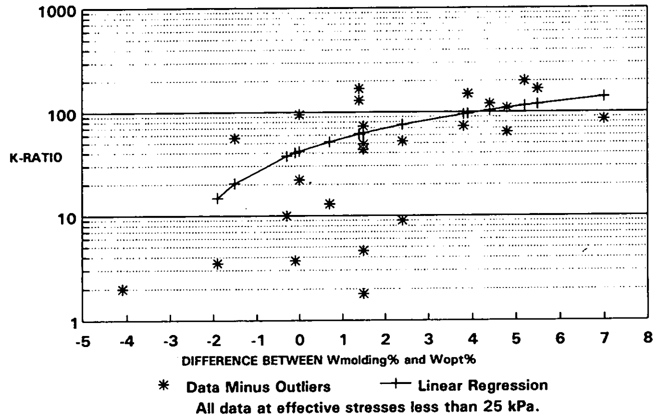

FIGURE 5 ***K*-ratio versus *w*% deviation from w_{opt}%: data minus outliers.**

1. All soil specimens exhibited an increase in hydraulic conductivity after being subjected to freeze/thaw conditions.
2. The availability of water during freezing strongly correlated with the magnitude of the increase in post-freeze/thaw hydraulic conductivity.
3. Soils compacted dry of optimum water content underwent (on the average) less than one order of magnitude increase in hydraulic conductivity, whereas soils compacted wet of optimum underwent (on mean) two orders of magnitude increase in hydraulic conductivity.
4. Increased effective stress in the soil specimens resulted in decreased magnitude of change in the post-freeze/thaw hydraulic conductivity. For effective stresses above approximately 70 kPa, the changes in hydraulic conductivity induced by the freezing action were nearly nullified.

The hypothesis that the severity of damage to the soil should correlate with the volume of water contained in the soil pores is supported by the data analyzed. All of the specimens were tested under closed-system conditions; that is, there was no source of water during freezing except for that already contained in the soil pores. Soils compacted wet of optimum, indicating a high degree of saturation, contained more water available during freezing, and the data show a marked increase in the subsequent hydraulic conductivity. Soils compacted dry of optimum, indicating less water available during freezing, showed smaller changes in post-freeze/thaw hydraulic conductivity.

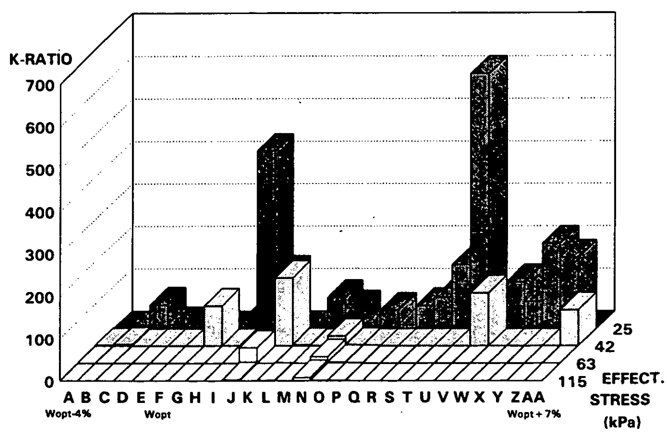

FIGURE 6 ***K*-ratio versus *w*% deviation from w_{opt}%: w_{opt} = *F*.**

In conclusion, when there is no other source of water, soils compacted dry of optimum may not be subject to significant freeze/thaw damage. This is especially likely in cases where an appreciable effective stress exists in the soil. However, in seepage containment applications, soils are most often compacted wet of optimum to minimize the hydraulic conductivity (*1,2,16*). It is in this state that damage due to freezing action is most pronounced. Thus, in situations where freezing conditions may develop, application of large confining stresses and compaction dry of optimum (while continuing to meet minimum hydraulic conductivity requirements) may help to safeguard against significant changes in hydraulic conductivity due to freezing action.

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