Freezing Induced Bulk Volume Changes in Compacted Clay Soils

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ABSTRACT
Overall soil shrinkage may occur during the freezing of non-rigid clay soils if the air filled pore volume is sufficient to accommodate ice growth. Bulk soil volume change was measured for seven soils, with clay contents ranging from 0.11 kg kg^{-1} to 0.75 kg kg^{-1}, and frozen at water contents of 10% to 95% saturation. Polynomial curve fitting revealed zones dominated by volumetric decreases and maximum shrinkage at water contents of 63% to 70% saturation, zero volume change at percent saturations of 74% to 90% and expansion at water contents above this level.

RÉSUMÉ
Dans l'ensemble, la contraction du sol peut survenir pendant le gel des sols argileux non rigides si le volume d'air des pores est suffisant pour contenir l'élargissement de la glace. La modification du volume brut du sol a été calculée pour sept sols dont les teneurs en argile oscillent entre 0,11 kg kg-1 et 0,75 kg kg-1 et congelés à des teneurs d'eau variant entre 10% et 95% de saturation. La courbe polynomiale adaptée a révélé des zones dominées par des diminutions volumétriques et un rétrécissement maximum en teneur d'eau de 63% à 70% de saturation, un volume de changement nul à des pourcentages de saturation de 74% à 90% et une expansion à des pourcentages de saturation supérieurs à ce niveau.

1 INTRODUCTION

Thermodynamic considerations dictate that temperature gradients across the freezing point within a soil mass result in the transport of pore water toward the cold side and any existing ice crystals. It is intuitive that at low water contents the soil pore system should be large enough relative to the volumetric expansion due to the phase change to ice to accommodate the effects of freezing. Theoretically, as pore water content surpasses 91.7% saturation, the 9.05% volumetric expansion upon the phase change from liquid water to ice should result in overall expansive effects on the soil due to freezing. In the extreme, when ice segregation occurs, soil volume increases are concomitant with the volumetric increase during the phase change of both the existing pore water upon freezing and any water drawn towards the growing ice lenses under open system conditions. Ice segregation is favoured in well graded silt soils where the typical pore size distribution provides the optimal combination of matric potential and hydraulic conductivity to facilitate pore water migration to a growing ice lens. The smaller pore sizes of clay rich soils, and their concomitant higher matric potential and lower hydraulic conductivity, typically exhibit more of a closed system with respect to freezing induced water migration (Rix 1969).

An aggregated soil mass is comprised of clusters of soil and a surrounding network of pores of varying sizes (Collins and McGown 1974; Delage and Lefebvre 1984). Inter-aggregate pore size and volume tends to be larger than intra-aggregate pore space and volume (Delage and Lefebvre 1984; Navarro and Alonso 2001). As freezing progresses in aggregated clay rich soils, the supply of readily frozen water from within the larger inter-aggregate pores is exhausted first. So long as a temperature gradient exists within the soil, negative pore water pressures resulting from water movement along the temperature gradient will extract water from progressively smaller pores (Everett 1961), including intra-aggregate pores, leading to an increase in the effective stress within the soil matrix (Williams 1963; Konrad 1989a), and particularly within the aggregates.

The presence of clay, particularly one which experiences desiccation induced shrinkage, exacerbates the situation as such soil does not exhibit a rigid matrix. The resulting shrinkage of the soil matrix is attributed to the rearrangement, and possibly consolidation, of the clay particles within the aggregates themselves (Penner 1963; Hamilton 1966; Richardson 1976; Othman and Benson 1993; Konrad 1989a, b; Konrad and Samson 2000). Overall shrinkage during the freezing process has been noted by Penner (1963), Richardson (1976), Chamberlain and Blouin (1978), Chamberlain and Gow (1979), Chamberlain (1981), Konrad (1989a, b), Othman and Benson (1993), and Konrad and Samson (2000), and cases of freezing induced ground settlement have been reported by Johnson (1952), Hamilton (1966), Hamilton (1963, 1982). This process has been called "cryogenical consolidation" by Hohmann (1977).

Volumetric increases of the bulk soil mass during frost heaving are typically viewed as being more destructive, particularly in terms of the engineering properties of the soil mass and have therefore been studied in greater detail. Although often noted, either implicitly or explicitly, in freezing studies, the ancillary process of freezing induced desiccation and shrinkage of smaller volumetric units, such as the soil between ice lenses or within aggregates, has received less attention. The objective of this study was to delineate the range of water contents under which bulk volume shrinkage dominated over bulk volume increases upon freezing in soils of varying clay contents and initial water contents.

2 MATERIALS AND METHODS

An extensive set of freezing induced volume change data in soils of varying clay contents was presented by Hamilton (1966). A series of plots of volume change upon freezing at different initial degrees of saturation were provided for five different soils (clay contents of 0.23, 0.32, 0.50, 0.55 and 0.75 kg kg^{-1}). Two soils from the Niagara Peninsula, Southern Ontario, were chosen to supplement this data set.

The soil with the lower clay content (0.11 kg kg^{-1}, designated C11), a sandy loam , and the soil with the higher clay content (0.33 kg kg^{-1}, designated C33), a clay loam, were sampled by shovel from the top 20 cm from the same vineyard in Niagara-on-the-Lake, Ontario.

In accordance with Hamilton's (1966) methodology, the standard effort test method (American Society for Testing and Materials (ASTM) Designation D 698-00a: Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort), commonly referred to as the Standard Proctor method, was used to compact the soils. A mould of dimensions 116.4 mm high, 101.6 mm diameter, fitted with a 60.3 mm extension ring was filled with soil in three successive layers of equal thickness. Each layer was compacted via 25 blows with a 24.4 N rammer dropped from a distance of 305 mm, resulting in a total compactive effort of approximately 600 kN·m·m^{-3} (ASTM 2000). Following compaction, the extension ring was removed, and the soil leveled with the top of the mould with a cutting edge.

Hamilton (1966) used samples of dimensions 101.6 mm long and 50.8 mm diameter in his freezing tests. To obtain samples of the same size, a 152.4 mm long and 50.8 mm diameter split spoon sampler was pressed downward into the compacted soil within the compaction mould. The filled sampler was excavated from the mould, the soil core removed, and the ends trimmed smooth and flat. Water content of the sample was determined from replicated measurements from these trimmings and from the soil remaining in the mould. Cores were placed between 50.8 mm diameter, 25.4 mm thick aluminum end caps and sealed in thin latex membranes. After a reference grid was marked on both the encapsulating membrane and the end caps to facilitate reproducible measurements, three measurements of diameter and four measurements of length of each core were made with precision calipers (0.02 mm precision) and core volume was calculated. This procedure was repeated for soil representing different water contents. The cores were placed in a refrigerator at 4°C for 24 hr to allow for any water content equilibration.

The methodology of Hamilton (1966) was used to subject the cores to uniaxial freezing from the top down. Each core was insulated at the sides and bottom by placing it in a 304.8 mm long, 152.4 mm diameter cardboard concrete cylinder mould filled with vermiculite insulation and capped at the top and bottom with 25.4 mm thick extruded polystyrene. To allow heat extraction from the core, a 25.4 mm diameter hole in the top polystyrene insulating cap in the cardboard cylinder exposed the core's aluminum top end cap to the -15°C atmosphere in the freezer. After 24 hr the cores were removed from the insulated cylinders, the dimensions measured while still in the frozen state and core volume calculated.

3 RESULTS

Hamilton (1966) presented a series of plots of volume change upon freezing at different initial degrees of saturation for five different soils. For one soil (GH, with 0.55 kg kg^{-1} clay content) two different freezing temperatures, -30.6°C (-23°F) and -6.7°C (+20°F), were used during the freezing tests. These results were presented as Figure 5 in the original paper.

For dry initial conditions, up to approximately 20% saturation, there is minimal volume change upon freezing at either freezing temperature. At very low water contents, virtually all pore water would be tightly held within the intra-aggregate pore space as adsorbed water films (Hamilton 1966) and would not be involved in the freezing process. As initial water contents at the time of freezing increase, a stronger effect is noted for the colder curve as the negative pore water pressures generated would also be greater (Everett 1961). The volume change curves for both temperatures show a decline to a minimum value as initial water contents at the time of freezing increase, representing a maximum amount of shrinkage. At these lower water contents, the volumetric expansion due to the phase change from water to ice is being fully accommodated by the existing pore volume and desiccation induced shrinkage of the soil mass is being realized. Further increases in water content at the time of freezing result in a steady rise of the curves representing the change in bulk soil volume as volumetric expansion effects associated with the phase change to ice begin to dominate over the effects of freezing induced desiccation and shrinkage as the initial empty pore volume is insufficient to accommodate the expansion.

The curves cross the zero volume change line at the degree of saturation where the effects of the freezing induced shrinkage mechanism and the volumetric expansion mechanism associated with formation of ice exactly balance, resulting in zero bulk volume change. With increasing initial water contents above 80% to 90% saturation, the expansion mechanism due to the freezing of water dominates resulting in increased bulk soil volume. Throughout the range of water contents from completely dry to 100% saturation, the colder curve generally shows greater effects, both shrinkage at lower water contents (below approximately 85% saturation) and expansion at higher water contents, than the warmer curve suggesting a greater proportion of the total pore water is involved in the freezing process.

The data from Hamilton's Figure 5 and that of four other soils, depicted in Figure 4 in the original paper, were extracted for the purpose of curve fitting to further analyze the volume change versus water content relationship, and to interpolate the effects at the intermediate temperature of -15°C used for the two additional soils. Curve fitting and data analysis were performed using Mathcad (MathSoft, Inc. 1999) and Minitab (Minitab, Inc. 2006) software.

3.1 Fitting Curves

3.1.1 The Cold Curve

The direction and magnitude of volumetric change for each of the two temperatures can be considered as the sum of two separate non-linear curves, each of which can be modeled separately by polynomial equations. The curve at lower water contents displays the dominant effect of freezing induced desiccation and shrinkage, while the curve at higher water contents depicts the dominant volumetric expansion effect associated with the phase change of water to ice under closed system freezing. The point at which the two curves meet represents maximum shrinkage and the water content at which the expansion effects begin to dominate over the shrinkage effects.

The data for the colder of Hamilton's (1966) two curves (-30.6°C or -23°F) corresponding to the lower degrees of saturation, before the minimum value of volumetric change was reached, was well represented by the following cubic polynomial equation:

$$VC_{CD} = -3.447\times10^{-5}\cdot PS^3 + 2.060\times10^{-4}\cdot PS^2 + 7.992\times10^{-3}\cdot PS \quad [1]$$

where VC_{CD} represents the volumetric change at the colder temperature and drier water contents, and PS represents percent saturation ($r^2 = 0.990$ and $p<0.001$). The absence of a constant in the polynomial fit for water contents at the dry end forces the fit through the origin as the a priori assumption is there is zero volumetric change at zero water content. The nature of the polynomial equation results in non-zero values of the curve between zero water content and the lowest data points. Theoretical considerations would suggest near zero or slightly negative volume change within this range as a result of the minimal pore water available for the freezing process. This was considered to be an acceptable limitation of the model given the interpolated nature of the fit within the drier range and the high quality of the fit through the actual data points.

The portion of the curve representing water contents higher than that corresponding to the minimum value of volumetric change was similarly well represented by the following quadratic polynomial equation:

$$VC_{CM} = -1.052\times10^{-2}\cdot PS^2 + 2.151\cdot PS - 1.066\times10^2 \quad [2]$$

where VC_{CM} represents the volumetric change at the colder temperatures and the wet end of the curve ($r^2 = 1.000$ and $p = 0.003$). The high r^2 value in this case is the result of fitting a quadratic equation through only four data points.

To construct a mathematical model for the complete shrinkage/expansion curve ranging from 0% to 100% saturation, the following combination of the two primary curves produced an accurate elegant fit:

$$VC_C = -\left[\left(\frac{1}{VC_{CD}}\right)^3 + \left(\frac{1}{VC_{CM}}\right)^3\right]^{-\frac{1}{3}} \quad [3]$$

where VC_C represents the volumetric change for the colder of the two curves.

To determine the percent of saturation at which the maximum shrinkage occurs and the effects of volumetric expansion begin to dominate over the shrinkage effects, the fitted volumetric change equation was differentiated with respect to the percentage of saturation to find the slopes and then equated to zero. Differentiation with MathCad revealed a maximum shrinkage of 7.4% occurring at 66.6% saturation.

3.1.2 The Warm Curve

Hamilton's (1966) data for the same experiment at the warmer temperature of -6.7°C (+20°F) was far less complete than that for the colder temperature of -30.6°C (-23°F) as volume change was measured at fewer water contents, particularly at the drier end. Hamilton's (1966) Figure 5 included a presumably qualitative curve fit to these data which closely resembled the curve fit to the colder freezing temperature data. These two qualitative curves, corresponding to the two freezing temperatures, suggested maximum shrinkage at approximately the same degree of saturation.

The limited data set of the warmer freezing temperature tests precludes the rigorous fitting of polynomial regression equations as was done for the colder curve. The three data points only allow the fitting of an equation with two coefficients. Hamilton (1966) suggested the effects of freezing at the two temperatures were essentially the same with the primary difference being that of the magnitude of the bulk volume change. As the objective of this study was to delineate the range of water contents under which bulk volume shrinkage dominated over bulk volume increases upon freezing, rather than fitting a precise model of the volume change versus water content relationship, it was felt that the same polynomial curve fitting exercise would suffice, even with the limited data set. Although the results carry limited statistical significance as a result of this constraint, it is felt they suggest a similarity in the freezing process at different temperatures thus justifying the exercise.

The data for the warmer of Hamilton's (1966) two curves (-6.7°C or +20°F) corresponding to the lower degrees of saturation, before maximum shrinkage was reached, were fitted with the following cubic equation:

$$VC_{WD} = -2.243\times10^{-5}\cdot PS^{3} + 0.118 \qquad [4]$$

where VC_{WD} represents the volumetric change at the warmer temperature and drier water contents ($r^2 = 0.952$ and $p = 0.099$). Similarly, the portion of the curve representing water contents higher than that corresponding to maximum shrinkage was fitted with the following quadratic equation:

$$VC_{WM} = -8.648\times10^{-3}\cdot PS^{2} + 1.785\cdot PS - 89.149 \qquad [5]$$

where VC_{WM} represents the volumetric change at the warmer temperatures and the wet end of the curve ($r^2 = 0.987$ and $p = 0.066$).

The VC_{WM} curve was fitted without one of the data points from Hamilton's (1966) Figure 5. The inclusion of the point representing the volumetric expansion corresponding to the highest degree of saturation resulted in a fitted line for the warmer temperature (-6.7°C) that failed to cross over the colder (-30.6°C) curve at the point of zero expansion. It can be intuitively argued that the greater amount of ice formation likely at the lower freezing temperature would result in a corresponding larger value of volumetric expansion, thus making this point an outlier. Realistically, however, most of the pore water that will ultimately freeze will likely have done so by -6.7°C, and little additional pore water will freeze by -30.6°C (Lovell 1957; Nerseova and Tsytovich 1963; Low et al. 1966; Anderson and Morgenstern 1973; Konrad and Samson 2000). Hamilton (1966) similarly noted that a large portion of the total dimensional change occurred by -6.7°C, during the initial freeze, and that comparatively little change occurred as the temperature continued to fall. Hamilton's (1966) Figure 2 also shows that there is an inconsistent relationship between length and diameter changes during freezing at higher water contents. While the percent length change increases consistently with increases in percent saturation at freezing temperatures, there is a greater percent change in diameter at 91.0% saturation than at 93.5% saturation. Further, the difference between the volume change values at the two temperatures amount to <0.5% suggesting that measurement precision or some unexplained variation may account for this small difference. As the purpose of the curve fitting exercise was to investigate at which water content the freezing induced shrinkage within the intra-aggregate pore space is balanced by the volumetric expansion of the bulk soil mass, rather than the maximum volumetric expansion at saturation, it was considered justifiable to delete this one data point from the analysis.

The complete curve for -6.7°C was constructed by using the same model used for the colder of the two curves (Eq. 4). Differentiation with MathCad revealed a maximum shrinkage of 6.8% occurring at 66.5% saturation.

3.1.3 Fitting the -15°C Curve

Data in the literature suggest that the quantity of unfrozen water content of a soil decreases rapidly with lower sub-zero temperatures, but soon reaches a fairly stable value whereby significantly lower temperatures result in very little additional freezing (e.g., Anderson and Morgenstern 1973; Konrad and Samson 2000). The use of excessively low temperatures under laboratory conditions also fails to realistically model the freezing conditions in the field. As the data from this study were part of a larger experimental program, the present experiments utilized a freezing temperature of -15°C. Although this temperature may commonly be attained at the soil surface, the soil temperature in Southern Ontario, at even shallow depths, rarely drops to more than -5°C (Phillips and Aston 1979). This minimum temperature is therefore a compromise between one that would allow the freezing of a substantial quantity of the pore water while still maintaining conditions that, although extreme, are not completely inconsistent with conditions experienced in the field.

The effects of this freezing temperature were interpolated from Hamilton's (1966) data for the GH soil at the two different freezing temperatures. The assumption was made that there would be no volumetric change under the conditions of a 0°C treatment as no pore water would freeze. This curve could now be viewed as depicting the effects of freezing at three separate temperatures (-30.6°C, -6.7°C and 0°C), between which the effects at -15°C could be interpolated. The effect of lower freezing temperatures was highly nonlinear, as at any given water content the volumetric change from 0°C to -6.7°C was clearly greater than the effect between -6.7°C and -30.6°C. The -6.7°C data shared common values for percentage saturation with the -30.6°C data, but with fewer values, so only those common to both temperatures were used in the interpolation process. These fewer data points limited the number of coefficients in the fitted curves, but adequate representation of the relationship was possible for the purposes of establishing the general relationship between volume change and water content at different freezing temperatures. Volumetric change values for -15°C corresponding to the common water contents for the -30.6°C and -6.7°C curves were interpolated via an exponential curve fit through the points corresponding to the three temperatures from Hamilton's (1966) original plot (-30.6°C, -6.7°C and 0°C). Although this procedure heavily weighs the effects of the -30.6°C and -6.7°C lines in the curve fitting procedure, the lack of data from other freezing temperatures limited the curve fitting options. Further, as the purpose of the exercise was to establish the point at which maximum shrinkage occurred, rather than the entire volume change versus water content relationship, it was felt that this procedure was justified. Once these points were established, a curve representing the volumetric change versus degree of saturation relationship was fitted for -15°C using the same procedure used for the -30.6°C and -6.7°C curves.

The dry end of the curve, before maximum shrinkage for the -30.6°C and -6.7°C curves was reached, was fitted with the following polynomial equation:

$$VC_{-15D} = -2.746\times10^{-5}\cdot PS^{3} + 6.390\times10^{-2} \qquad [6]$$

where VC_{-15D} represents the volumetric change at -15°C and drier water contents (r^2 = 0.991 and p = 0.042). Similarly, the portion of the curve representing water contents higher than that corresponding to the minimum value of volumetric change for the -30.6°C and -6.7°C curves was fitted with the following quadratic equation:

$$VC_{-15M} = 2.518\times10^{-3}\cdot PS^{2} - 18.670 \qquad [7]$$

where VC_{-15M} represents the volumetric change at -15°C for the wet end of the curve (r^2 = 0.949 and p = 0.102).

The complete interpolated curve for -15°C was constructed using the same model used for both the cold and warm curves from Hamilton's (1966) data (Eq. 3). Maximum volumetric expansion at 100% saturation is estimated to be 3.3%, which is precisely the same value as calculated for the -30.6°C curve. Zero volumetric expansion is calculated to occur at 84.5% saturation, which also closely corresponds to the values obtained for the -30.6°C curve. Differentiation of the -15°C curve using MathCad yields an equation of the same structure as the one for the colder of the two curves, and reveals a maximum shrinkage of 7.54% occurring at 66.69% saturation, again in close agreement with values calculated for the -30.6°C curve.

Figure 1 illustrates the curves fit to Hamilton's (1966) volume change data for both the -30.6°C and -6.7°C treatments and the interpolated values for -15°C. The interpolated line for -15°C would be expected to lie between the lines representing the higher and lower temperatures, and this is generally the case, and particularly so for water contents below that corresponding to maximum shrinkage. Slight disagreement between the interpolated line for -15°C and the -30.6°C curve exists in the vicinity of the maximum shrinkage, where the interpolated curve lies slightly below the curve fitted to Hamilton's (1966) data. It is assumed that freezing at the lowest temperature would result in greatest shrinkage as the extraction of water from the pore system towards zones of freezing would be maximized by the cold temperature. One would therefore assume maximum shrinkage point on the -15°C curve would lie between corresponding points of the -30.6°C and -6.7°C lines. The scarcity of original data in this critical area of the curve means the procedure for fitting both the individual curves through both the dry and wet ends of Hamilton's (1966) data, and the combination of these curves, cannot take into account any specific point of maximum shrinkage but must strictly estimate this value from widely separated data points on either side. Similarly, the point of maximum shrinkage for the -15°C line is simply the result of the mathematical combination of the individual curves fitted to the dry and wet ends of the data interpolated from the data extracted from Hamilton (1966). The slight disagreement at the point of maximum shrinkage is therefore mathematically based and does not suggest an inconsistency in the effects of the freezing process at this particular water content. At water contents above that corresponding to maximum shrinkage, the interpolated -15°C line and the -30.6°C curve quickly converge and almost coexist through the cross-over point, after which the effects of volumetric expansion associated with the phase change to ice results in greater percent volume change at lower temperatures.

3.1.4 Results from the C11 and C33 Soils

Curves were fitted to the volume change data for the two soils in the same manner as for Hamilton's data. The data for the C33 soil corresponding to the lower degrees of saturation, before the minimum value of volumetric change was reached, was well represented by a cubic polynomial equation. The data for the higher degrees of saturation, after the minimum value of volumetric change was reached, was well represented by a quadratic polynomial equation. These two segments of the curve were fitted in the same manner as in Equation 3, and analysis revealed maximum shrinkage of 1.70% at 69.13% saturation.

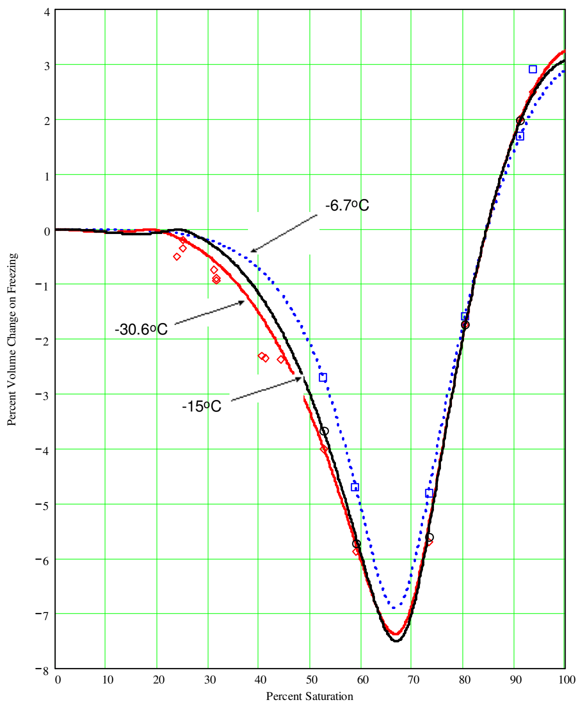

Figure 1: Fitted Curves for Hamilton's (1966) Data and the Interpolated –15°C Curve

The data for the C11 soil corresponding to the lower degrees of saturation, before the minimum value of volumetric change was reached, was well represented by a quadratic polynomial equation. The data for the higher degrees of saturation, after the minimum value of volumetric change was reached, was well represented by a quadratic polynomial equation. These two segments of the curve were fitted in the same manner as in Equation 3, and analysis revealed maximum shrinkage of 1.28% at 65.91% saturation.

Curves for both soils displayed shapes similar to those derived from Hamilton's (1966) data. At lower percentage saturation values there was little volume change, presumably as there is very little pore water to freeze and cause an alteration of the soil volume. However, as water content increases, rather than seeing an increase in soil volume due to the volumetric increase as liquid water freezes to ice, a decrease in soil volume becomes evident regardless of the soil. Shrinkage continues with increasing water content until a minimum bulk volume is attained. Maximum shrinkage occurs at similar percentage saturation values regardless of soil, ranging from 63.39% for Hamilton's A5 soil (0.50 kg kg^{-1} clay) to 69.13% for the C33 soil (0.33 kg kg^{-1} clay). The greatest shrinkage ranges from -10.12% volumetric change for Hamilton's TH soil, with a clay content of 0.75 kg kg^{-1}, to -1.28% volumetric change for the C11 soil, with a clay content of 0.11 kg kg^{-1} (Table 1). A significant linear relationship exists between volumetric change and clay content ($p = 0.004$). As water content increases beyond these values, expansion begins to dominate and all curves show an upward trend, eventually crossing the zero volumetric change line and approaching a maximum value.

Table 1. Analysis of volumetric change fitted curves

Soil	Clay Content (kg kg^{-1})	Minimum %VC	% Sat @ Min %VC	% Sat @ VC = 0%	Max. %VC
C11	0.11	-1.28	65.91	74.47	3.09
A2	0.23	-3.84	65.03	87.10	15.32[z]
A11	0.32	-5.87	66.76	81.02	2.74
C33	0.33	-1.70	69.13	79.22	3.50
A5	0.50	-7.77	63.39	82.15	2.83
GH[y]	0.55	-7.54	66.69	84.96	2.92
TH	0.75	-10.12	68.52	89.76	4.63[z]

[z] Unrealistic value due to curve fitting limitations
[y] Interpolated at -15°C

The fitted volume change curves reveal that once expansion begins to dominate following the shrinkage at lower water contents, zero volumetric change occurs within a narrow range of water contents. Regression analysis reveals a relationship between the percentage saturation at zero volumetric expansion with clay content ($p = 0.068$), although there is considerable spread within the data ($r^2 = 0.518$). The soil with the lowest clay content, C11 (0.11 kg kg^{-1} clay), crossed the zero volumetric change line at 74.47% saturation while the TH soil (0.75 kg kg^{-1} clay), crossed at a calculated value of 89.76% saturation (Table 1). The C33 soil (0.33 kg kg^{-1} clay), with a texture falling within the range of Hamilton's (1966) soils, experienced zero volume change at a calculated value of 79.22% saturation, which is very comparable to Hamilton's A11 soil (0.32 kg kg^{-1} clay), which experienced zero volume change at a calculated value of 81.02% saturation.

Theoretical considerations dictate that once percentage saturation surpasses 91.7%, the 9.05% volumetric expansion associated with the phase change from water to ice would result in volumetric expansion of the soil cores as the remaining unfilled pore volume would be insufficient to accommodate the ice growth. Implicit in this is the assumption that the pore network within the soil remains unchanged during the freezing process. This cannot be the case however as this would in itself preclude the freezing induced shrinkage noted in all soils. Rather, there is likely a balance between volumetric expansion and freezing induced desiccation and shrinkage within the soil matrix at saturation levels approaching the theoretical limit of 91.7%. This process is consistent with observations of a nuggetty structure following the freezing and thawing of initially unstructured clays as zones of desiccation induced shrinkage produce stable aggregates which in turn are surrounded by failure zones delineating the locations of ice (Chamberlain and Gow 1979; Graham and Au 1985; Leroueil et al. 1991).

The maximum values of volumetric expansion may also be estimated from the fitted curves. Again, these fall within a narrow range, from 2.74% for the A11 soil (0.32 kg kg^{-1} clay) to 4.63% for the TH soil (0.75 kg kg^{-1} clay) (Table 1). This last value is suspect, as is the 15.32% for the A2 soil (0.23 kg kg^{-1} clay) thus reflecting the limitations and dangers of extrapolation of fitted curves beyond the upper range of the data. These values more closely reflect the mathematical limitations of the curve fitting procedure than any actual physical process in the freezing soil. Even after discounting the two suspect values for the A2 and TH soils, no relationship was found between maximum volumetric expansion and clay content ($p = 0.602$), plastic limit ($p = 0.958$) or plasticity index ($p = 0.174$).

4 DISCUSSION

The initial constant water content during freezing controls the direction and magnitude of volume changes. The bulk soil volume changes associated with the freezing process comprises three separate phases dependent on the water content at the time of freezing.

Under very dry conditions, where there is very little water available to either freeze or migrate toward growing ice crystals, volumetric change, expressed as either expansion or shrinkage, is minimal.

Once a certain threshold degree of saturation is reached, volume decreases are noted as the shrinkage of the soil mass as a result of desiccation dominates over the expansion associated with the phase change from water to ice. At these higher water contents less tightly held water within larger pore spaces begins to freeze as temperature falls. Below a certain degree of saturation, the air-filled pore space is sufficiently large to accommodate the volumetric expansion associated with the phase change from liquid water to ice. At the same time, water migration under the influence of very high negative pore water pressures associated with the growing ice crystals causes a desiccation induced consolidation of the clay matrix, with the net effect being a bulk volume decrease associated with the freezing process. The shrinkage process becomes more pronounced as initial water content increases, with further increases leading to non-linear increases in shrinkage until initial water contents at freezing reach much higher levels nearing two thirds of the available pore space.

At these much higher initial water contents a different physical phenomenon begins to have an effect on bulk soil volume. As larger pores begin to fill with water and there exists less air-filled pore space to accommodate the volumetric expansion associated with the formation of ice, increased shrinkage begins to be compensated by the volumetric increase of water upon conversion to ice. This effect has an increasingly dominant influence on the bulk soil volume as further increases in initial water content leads to a shift in the balance between shrinkage and expansion effects (i.e., expansion effects begin to overtake shrinkage effects). There exists a water content where freezing induced shrinkage from the desiccation of the smaller pore space is balanced by the volumetric expansion of the bulk soil mass. Thus, there exists a state of zero freezing induced bulk volume change despite the seemingly high initial water content (74% - 90% saturation). With further increases in the initial water content the phenomenon of volumetric expansion of water freezing to ice begins to dominate.

Hamilton's original curves demonstrate a greater effect on volumetric change with lower freezing temperatures. For the portion of the two curves where the volumetric change is negative, the colder temperature curve lies below the curve for the warmer temperature at lower water contents. For the portion of the two curves showing volumetric expansion, the curve for the colder temperature is calculated as lying above the curve for the warmer temperature at higher water contents. Maximum volumetric expansions experienced at 100% saturation values were 3.3% and 2.9% for the -30.6°C and the -6.7°C fitted lines, respectively. The cross over point of the curves for the two temperatures occurs at approximately the same percentage saturation corresponding to the transition from shrinkage to expansion, or zero volumetric change (Figure 1). Analysis of the fitted equations revealed that these percentage saturation values corresponding to zero volumetric change were 84.5% and 84.3% for the -30.6°C and the -6.7°C lines, respectively.

That the volumetric expansion curves corresponding to these two freezing temperatures are in general agreement across the entire range of water contents suggests a similarity in the effects of the freezing process, with the only difference being that of the magnitude of the effect. Hamilton (1966) attributed the greater shrinkage at the lower temperature to a greater percentage of the total volume of pore water migrating outward from the progressively smaller pores and freezing at the lower temperature, hence contributing to the desiccating effect of freezing. Similarly, the greater expansion at higher saturation suggests a greater quantity of pore water freezing at lower temperatures. Analysis of the fitted curves, however, shows that the effect of freezing temperature is minimal. In the case of the volume change, both at maximum shrinkage and maximum expansion, the difference is only in the order of 0.5%. Konrad and Samson (2000) suggest that freezing-related void ratio changes are not associated with a specific minimum temperature, but more to the temperature at which no further changes in the unfrozen water content are realized, which they suggest is approximately -2EC. Anderson and Morgenstern (1973) provide data showing this temperature to be approximately -8EC for a clay, while Bryan (1971) found that a minimum temperature of between -11EC and -25EC was required with finer-textured soils requiring lower temperatures than coarser soils. Although limited data precludes a more thorough analysis, this difference is likely well within the limits of error suggesting that the freezing temperature of -15EC did not play a major role in determining the magnitude of volume change upon freezing.

Although the ultimate freezing temperature likely does not play an important role in the magnitude of freezing induced shrinkage, so long as it is sufficiently low enough to freeze the majority of pore water, the freezing rate is probably much more important. Particularly in the case of clay rich soils, with their typically low hydraulic conductivities, the longer time facilitated by a slower freezing rate is required for pore water to be drawn towards zones of ice nucleation thus allowing the effects of desiccation to be more fully felt. The role of freezing rate is particularly important in considering the efficacy of this process in the field as temperature gradients are the steepest close to the soil surface and generally decrease with depth. Freezing induced desiccation and shrinkage may therefore be a more important process slightly under the soil surface rather than at the surface.

Soil texture appears to play the major role in controlling the amount of volumetric change occurring during the freezing process. A significant negative relationship existed between the maximum shrinkage and soil texture as it was found that greater shrinkage occurred in the soils with the highest clay contents (p = 0.004). Hamilton's (1966) soils were dominated by montmorillonite and illite, with small amounts of kaolinite and chlorite in all soils. Both the C11 and C33 soils were dominated by vermiculite. This suggests the swelling behaviour of the soils may be an important control. However, analysis of variance found that soil consistency, as reflected in the plastic limits of the soils, was not found to be a significant factor (p = 0.673) while the texture, as reflected in the clay content, was a significant factor ($p = 0.010$). The lack of variety in clay mineralogy, particularly in terms of swelling versus non-swelling clays, within the soils reported upon in this study precludes identifying this as a control. The plasticity of the soils, as determined by the Atterberg limits, was similarly not sufficient to identify any controls on the process associated related to clay mineralogy. Further research is needed to identify the controls on this process related to clay mineralogy, plasticity and shrinkage.

5 CONCLUSIONS

The initial water content at the time of freezing controls the magnitude and direction of the volume change. At a certain water content at the time of freezing, representing approximately 63% to 70% saturation, the expansion effects due to the growing ice begin to dominate over desiccation induced shrinkage and the slope of the volume change curve becomes positive. A point of zero volume change typically occurs at levels of saturation ranging from 74% to 90%. At water contents higher than this, increases in soil bulk volume are realized.

Although there is a greater volume change effect at lower temperatures, the effect of freezing temperature is minimal. The freezing rate is likely a more important control as fast freezing limits the time available for water movement through the pore system to the freezing front.

Soil texture is an important control as the soils with the highest clay contents exhibited the greatest volume changes, although the roles of plasticity and mineralogy remain unclear.

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