Cyclic Freezing and Thawing Effects on Atterberg Limits of Clay Soils

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ABSTRACT
Several previous studies suggest Atterberg limits may change as a result of mechanical disruption. This study tests the hypothesis that liquid and plastic limits may be altered by the cyclic freezing and thawing process. Four soils with different clay contents were used. In one group of samples initial structure was maintained while a second group were ultrasonically dispersed at a high water content. Cyclic freezing at -15°C for 6 hr and thawing at +15°C for 6 hr was performed for 1, 5, 10, and 25 cycles at 25% gravimetric water content. Both liquid limits and plastic limits showed increases with an increasing number of freeze/thaw cycles for the structured soils but decreases in both limits for the unstructured soils. However, regression analysis revealed that the slopes of these relationships did not significantly differ from zero suggesting no effect of cyclic freezing and thawing on soil plasticity.

RÉSUMÉ
Plusieurs études précédentes ont suggéré que les limites d'Atterberg pouvaient être modifiées par la perturbation mécanique. La présente étude vérifie l'hypothèse selon laquelle les limites de liquidité et de plasticité pourraient être modifiées par un processus cyclique de gel et dégel. Quatre types de sols à fraction argileuse différente ont été testés. La structure initiale d'un premier groupe d'échantillons est demeurée la même, alors que celle d'un second groupe, dont la teneur en eau était élevée, a été dispersée par ultrasons. Des cycles de gel à -15°C pendant 6 heures et dégel à +15°C pendant 6 heures ont été répétés 1, 5, 10 et 25 fois à une teneur en eau gravimétrique de 25 %. Les limites de liquidité et de plasticité des sols structurés ont augmenté selon le nombre de cycles de gel et dégel exercés, mais les mêmes limites ont diminué dans les sols non structurés. Par contre, une analyse de régression a révélé que ces courbes de résultats ne s'éloignaient pas de zéro de manière assez significative pour conclure que des cycles de gel et dégel répétés ont un effet réel sur la plasticité du sol.

1 INTRODUCTION

Atterberg limits are used widely in the preliminary stages of design in civil and geotechnical engineering, with the liquid and plastic limits routinely quoted in the characterization of a clay soil. The liquid limit, for example, can be correlated with the coefficient of consolidation (e.g., Swan et al., 2013) and the plastic limit with compaction characteristics and the optimum water content (e.g., Kozlowski, 2009).

Implicit in this practice is that these limits are constant properties inherent to a particular soil. Some evidence exists in the literature suggesting that these limits may not, in fact, be constant but can change as a result of a disturbance to the soil. Torrance (1975) suggests that any process acting to disturb natural physical inter-clay particle relationships will in turn disturb the mechanical properties of the clay.

Freezing and thawing is one such process that has been studied extensively. Often considered to manifest itself primarily through frost heaving, this process can also affect, and be affected by, the fabric or structure of the soil. Thermodynamic considerations dictate that as the 0°C isotherm penetrates the soil ice crystals will form first within the largest voids. As the temperature falls further, unfrozen pore water migrates towards and feeds the growing ice crystal. Concomitant with this process is the progressive desiccation and increased effective stress leading to consolidation of the surrounding soil mass (Chamberlain, 1981; Knutsson, 1984; Graham and Au, 1985; Swan and Greene, 1998; Dagesse, 2010, 2013). Pre-existing fabric or structure, typically prevalent at the surface and resulting from soil forming factors, can potentially collapse through freezing induced desiccation (Knutsson, 1984; Graham and Au, 1985; Yong et al., 1985; Qi et al., 2006). Conversely, previously unstructured soils are often noted to develop a "nuggety" or crumbly structure following freezing and thawing via the same process of localized desiccation (e.g., Yong et al., 1982, 1985; Vähäaho, 1988; Swan and Greene, 1998). The intensity of this process may be such that pore water is drawn from sufficiently small pores or even the diffuse double layer surrounding the clay minerals (e.g., Lincoln and Tettenhorst, 1971; Yong et al., 1982; Pardini et al., 1995; Hohmann-Porebska, 2002). If pore water is unable to re-occupy these spaces upon thawing due to either pore collapse or a limited time before measurement, an observed and possibly irreversible change in Atterberg limits may result (Sangrey et al., 1976; Knutsson, 1984).

Controversy exists in the literature regarding the net effect of the freeze-thaw process on both the liquid and plastic limits. Decreases in the liquid limit following freezing and thawing are commonly noted (e.g., Knutsson, 1984; Aoyama et al., 1985; Yong et al., 1982, 1985; Vähäaho, 1988; Roy et al., 1995; Swan and Greene, 1998; Swan et al., 2013). Fewer studies report changes to the plastic limit. Swan and Greene (1998) and Swan et al. (2013) noted a small drop after one freeze-thaw cycle while Roy et al. (1995) found the plastic limit remained essentially unchanged. Others have reported no significant changes in liquid or plastic limits as a result of freezing and thawing although they do note changes in overall plasticity as characterized by the liquidity index (Eigenbrod, 1996) or plasticity index (Leshchikov and Ryashchenko, 1973).

At least part of this controversy may relate to the initial structural state of the soil. Pre-design testing may be carried out on soil samples obtained from the surface, while construction or excavation commonly exposes soils that may not have experienced present surface weather conditions, including the potentially deleterious effects of freezing and thawing (Baracos et al., 1980). Potential differences resulting from pre-existing structure may confound the net effect of freezing and thawing.

The purpose of this study was to investigate the effects of cyclic freezing and thawing on the Atterberg liquid and plastic limits on soils of differing clay contents and initial structural state.

2 MATERIALS AND METHODS

Four soils of varying clay content, ranging from 11% to 49%, were used to assess the effects of cyclic freezing and thawing. All soils were sampled from the former lakebed of proglacial Lake Iroquois in the Niagara Peninsula of Southern Ontario. It was felt that sampling from the same geomorphological setting would inherently minimize sample variation, including clay mineralogy, aside from the different clay contents. Sampling was from the top 20 cm bare soil surface of operational vineyards. The properties of these soils are summarized in Table 1.

Table 1. Initial Soil Properties (before Freeze/Thaw)

Soil Classification	Clay Content (%)	Liquid Limit (%)	Plastic Limit (%)
Gleyed Luvisol	11	23.59	18.06
Gleysol	33	38.43	22.15
Gleyed Luvisol	38	35.10	23.37
Gleysol	49	49.03	25.98

In order to assess the role of initial soil structure, two separate samples of each soil were used. The structured samples were comprised of natural soil aggregates resulting from natural pedalogical processes. They were subjected to cyclic freezing and thawing in the same state as when sampled. The unstructured samples were sub-sampled from the structured samples to ensure sample homogeneity. They were ultrasonically dispersed at high water content (100 g soil per litre of water) via the methodology outlined by Johnson and Moston (1976). Both the structured and unstructured samples were adjusted to a gravimetric water content of 25% prior to cyclic freezing and thawing. Samples were placed in dishes and sealed in airtight plastic bags before placement in the freezing chamber.

The temperature cycling involved 6 hours of freezing to -15°C followed by 6 hours of thawing at +15°C under closed system conditions (i.e., no access to additional free water). Periodic checks revealed that the water content was maintained over the course of the experiment. Monitoring of the internal sample temperatures revealed close agreement with those of the chamber.

Liquid and plastic limits were determined for all samples before the commencement of freezing and thawing (0 cycles) and following 1, 5, 10 and 25 freeze/thaw cycles. Liquid and plastic limits were determined via the methodology specified in ASTM D4318-10e1 (ASTM, 2010).

3 RESULTS

In order to assess the effects of cyclic freezing and thawing on the liquid and plastic limits of the samples, various statistical methods were employed.

3.1 Analysis of variance

Analysis of variance was used to assess the role of clay content, initial structure and the number of freezing and thawing cycles on both the liquid and plastic limits. This analysis revealed that, for the overall data set (i.e., 4 clay contents, 2 structural classes and cyclic freezing and thawing) only the clay content was a significant factor for both the liquid and plastic limits (Tables 2 & 3). The data set was separated by structural class for further analysis.

Table 2. Initial Analysis of Variance - Liquid Limit

Source	DF*	SS*	MS*	F*	p*
Clay Content	3	2807.26	935.75	42.73	0.000
Soil Structure	1	2.55	2.55	0.12	0.735
# F/T Cycles	4	17.62	4.40	0.20	0.936
Error	31	678.86	21.90		
Total	39	3506.29			

DF: degrees of freedom; SS: sum of squares; MS: mean square; F: F-value: p: p-value

Table 3. Initial Analysis of Variance - Plastic Limit

Source	DF*	SS*	MS*	F*	p*
Clay Content	3	343.48	114.49	35.19	0.000
Soil Structure	1	5.29	5.29	1.63	0.212
# F/T Cycles	4	16.24	4.06	1.25	0.311
Error	31	100.86	3.25		
Total	39	465.86			

DF: degrees of freedom; SS: sum of squares; MS: mean square; F: F-value: p: p-value

The liquid limit has often been found to change as a result of freezing and thawing (e.g., Knutsson, 1984; Aoyama et al., 1985; Yong et al., 1982, 1985; Vähäaho, 1988; Roy et al., 1995; Swan and Greene, 1998; Swan et al., 2013). Although soil structure and number of freezing and thawing cycles were not found to be significant factors in the overall analysis, analysis focussed on each structural state separately revealed both clay content and the number of freezing and thawing cycles were highly significant factors (Tables 4 & 5). This was the case for both the structured and unstructured soils.

Table 4. Analysis of Variance - Liquid Limit (naturally structured soil)

Source	DF*	SS*	MS*	F*	p*
Clay Content	3	1630.15	543.38	560.38	0.000
# F/T Cycles	4	27.81	6.95	7.17	0.003
Error	12	11.64	0.97		
Total	19	1669.60			

DF: degrees of freedom; SS: sum of squares; MS: mean square; F: F-value: p: p-value

Table 5. Analysis of Variance - Liquid Limit (unstructured soil)

Source	DF*	SS*	MS*	F*	p*
Clay Content	3	1709.49	569.83	131.63	0.000
# F/T Cycles	4	72.70	18.18	4.20	0.024
Error	12	51.95	4.33		
Total	19	1834.14			

DF: degrees of freedom; SS: sum of squares; MS: mean square; F: F-value: p: p-value

Changes to the plastic limit following freezing and thawing have been less commonly reported in the literature. The same general pattern found in the case of the liquid limit was found in the case of the plastic limit. Although soil structure and number of freezing and thawing cycles were not found to be significant factors in the overall analysis, for both the structured and unstructured samples taken separately, the clay content and number of freezing and thawing cycles were both found to be highly significant factors (Tables 6 & 7).

Table 6. Analysis of Variance - Plastic Limit (naturally structured soil)

Source	DF*	SS*	MS*	F*	p*
Clay Content	3	174.60	58.20	127.11	0.000
# F/T Cycles	4	25.16	6.29	13.74	0.000
Error	12	5.50	0.46		
Total	19	205.25			

DF: degrees of freedom; SS: sum of squares; MS: mean square; F: F-value: p: p-value

The different responses of the structured and unstructured samples to cyclic freezing and thawing likely resulted in their lack of significance in the original analysis. Statistical significance resulting from analysis within structural class suggested further analysis via linear regression.

Table 7. Analysis of Variance - Plastic Limit (unstructured soil)

Source	DF*	SS*	MS*	F*	p*
Clay Content	3	228.14	76.05	70.43	0.000
# F/T Cycles	4	14.22	3.55	3.29	0.049
Error	12	12.96	1.08		
Total	19	255.32			

DF: degrees of freedom; SS: sum of squares; MS: mean square; F: F-value: p: p-value

3.2 Regression analysis

Changes in the liquid and plastic limits of the four soils within each of the two structural states resulting from cyclic freezing and thawing are depicted in Figures 1-4.

Although not readily visible in the plots, both the liquid and plastic limits of the unstructured samples were generally higher than those of the structured samples (Table 8). The one noticeable exception was in the case of the highest clay content soil where values were marginally lower. This trend generally persisted throughout the course of freezing and thawing.

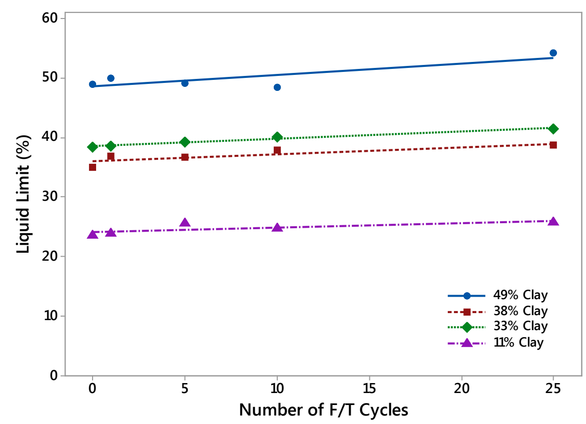

Figure 1. Liquid limit vs. number of freeze-thaw cycles (naturally structured soils)

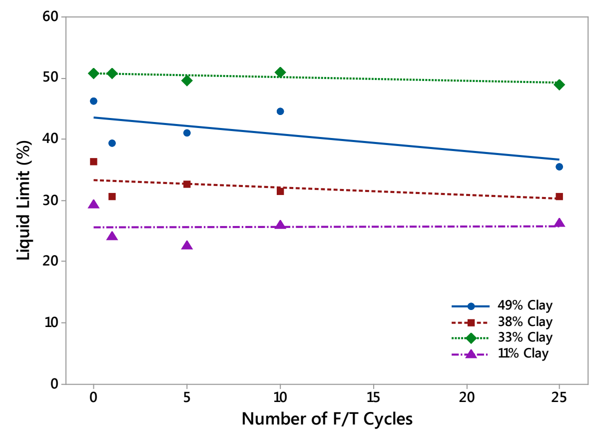

Figure 2. Liquid limit vs. number of freeze-thaw cycles (unstructured soils)

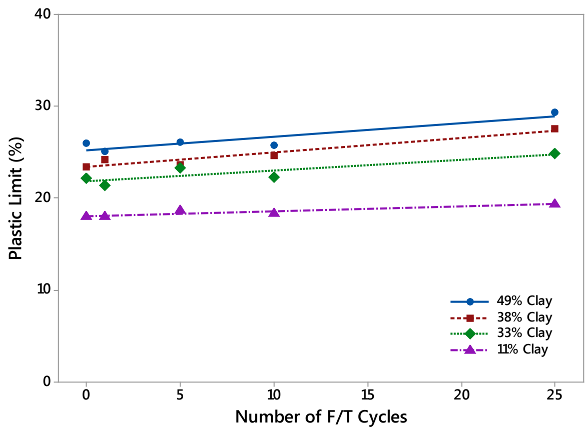

Figure 3. Plastic limit vs. number of freeze-thaw cycles (naturally structured soils)

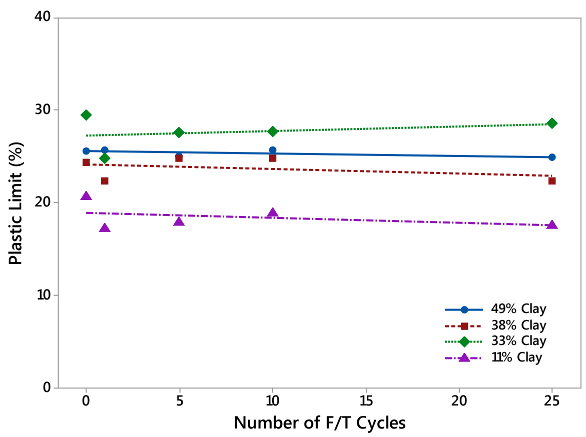

Figure 4. Plastic limit vs. number of freeze-thaw cycles (unstructured soils)

Table 8. Initial liquid and plastic limits for structured and unstructured samples

Clay Content (%)	Initial Liquid Limit (%)		Initial Plastic Limit (%)	
	S*	US*	S*	US*
11	23.59	29.41	18.06	20.77
33	38.43	50.85	22.15	29.54
38	35.10	36.39	23.37	24.42
49	49.03	46.30	25.98	25.58

* S: structured soils; US: unstructured soils

Cursory examination of Figures 1-4 suggests cyclic freezing and thawing increases both the liquid and plastic limits of structured soils while decreasing them in the unstructured samples. The effect is much more visually pronounced via the slopes of the trend lines in the case of structured soils (Figures 1 and 3) than in the very flat slopes of the unstructured soils (Figures 2 and 4). The different intercepts (statistically significant at $p<0.05$) confirm the expected dependency of both the liquid and plastic limits on clay content. The parallel nature of the lines (statistically significant at $p<0.05$) suggests a similar effect of cyclic freezing and thawing across all clay contents.

This is further suggested by macroscopic observation of the samples following freezing and thawing. By 10 cycles the original structure of the samples appeared to have been altered. The structured samples showed signs of breakdown into smaller aggregates while the originally unstructured samples began to assume a nuggety structure as frequently noted in the literature (e.g., Leshchikov and Ryashchenko, 1973; Chamberlain and Gow, 1979; Benson and Othman, 1983; Graham and Au, 1985; Yong et al., 1985; Vähäaho, 1988; Konishchev and Rogov, 1993; Eigenbrod, 1996; Swan and Greene, 1998; Qi et al., 2006).

Statistical analysis of the regression lines, however, reveals that these effects are not all statistically significant. In the case of the liquid limit, significant relationships are generally found only in the case of the structured soils (Table 9). The exception to this is the soil with the lowest clay content - the least plastic soil. The relationship between liquid limit and number of freezing and thawing cycles was not statistically significant in the case of the originally unstructured soils. A similar pattern was noted in the case of the plastic limit where the regressions were statistically significant for the structured soils but not significant for the initially unstructured soils (Table 10). Thus, although the plots and corresponding regression equations indicate generally consistent relationships, i.e., positive in the case of structured soils and negative for the unstructured soils, these relationships are not always statistically significant. The variability in the results between the structured and unstructured samples are likely the cause of the non-significance of the number of freezing and thawing cycles in the analysis of variance for the whole data set.

Examination of Figure 2 and Figure 4 reveals a pattern in the response of the liquid and plastic limits to the effects of freezing and thawing of the unstructured samples. An initial decrease following the first freezing and thawing cycle was noted followed by a general increase throughout five and ten cycles. This is consistent with other researchers who have generally found the largest effect after the first freezing and thawing cycle (e.g., Eigenbrod, 1996; Roy et al., 1995; Swan and Greene, 1998; Swan et al., 2013). By the end of 25 freezing and thawing cycles a generally decreasing trend was observed. This general pattern was not noted for the structured samples.

A more rigorous examination of the regression lines, however, showed that although the number of freezing and thawing cycles were generally significant factors in explaining the changes in both the liquid and plastic limits, a test of zero slopes revealed non-significant relationships (Table 11).

Although it would be tempting to analyze the data through non-linear regression techniques, the small number of data points would yield statistically questionable results. An extension of the study beyond 25 freeze-thaw cycles would yield more data to facilitate this type of analysis.

Table 9. Regression equations for liquid limit vs. number of F/T cycles

Clay Content	Structural State*	Liquid Limit	p-Value†
49	S	LL = 48.643 + 0.1889 F/T	0.080
38	S	LL = 36.153 + 0.1150 F/T	0.063
33	S	LL = 38.575 + 0.1258 F/T	0.003
11	S	LL = 24.203 + 0.0739 F/T	0.132 NS
49	US	LL = 43.650 - 0.2800 F/T	0.216 NS
38	US	LL = 33.410 - 0.1240 F/T	0.360 NS
33	US	LL = 50.732 - 0.0613 F/T	0.194 NS
11	US	LL = 25.670 + 0.0050 F/T	0.973 NS

* S: structured soils; US: unstructured soils
†: NS: not statistically significant

Table 10. Regression equations for plastic limit vs. number of F/T cycles

Clay Content	Structural State*	Plastic Limit	p-Value†
49	S	PL = 25.254 + 0.1480 F/T	0.028
38	S	PL = 23.380 + 0.1604 F/T	0.009
33	S	PL = 21.858 + 0.1143 F/T	0.048
11	S	PL = 18.094 + 0.0524 F/T	0.023
49	US	PL = 25.609 - 0.0245 F/T	0.213 NS
38	US	PL = 24.184 - 0.0478 F/T	0.517 NS
33	US	PL = 27.250 + 0.0525 F/T	0.618 NS
11	US	PL = 18.950 - 0.0537 F/T	0.521 NS

* S: structured soils; US: unstructured soils
†: NS: not statistically significant

Table 11. Test of slope = 0 for regression equations for plastic limit vs. number of F/T cycles

Structural State*	Clay Content (%)	Test of Slope = 0 p-Value† Liquid Limit (%)	Plastic Limit (%)
S	49	0.126 NS	0.117 NS
	38	0.129 NS	0.113 NS
	33	0.129 NS	0.120 NS
	11	0.130 NS	0.131 NS
US	49	0.189 NS	0.152 NS
	38	0.169 NS	0.158 NS
	33	0.153 NS	0.137 NS
	11	0.147 NS	0.164 NS

* S: structured soils; US: unstructured soils
†: NS: not statistically significant

4 DISCUSSION OF RESULTS

Freezing and thawing, particularly in the context of frost heaving, is commonly perceived as a destructive agent in terms of the mechanical properties of soil. Previous research, however, suggests that the migration of pore water, leading to localized zones of desiccation and consolidation via freezing induced suction (i.e., between ice lenses), may actually act in a constructive manner, albeit on a smaller scale than the entire soil mass (e.g., Chamberlain, 1981; Knutsson, 1984; Graham and Au, 1985; Dagesse, 2010, 2013). Although a larger scale soil mass such as the soil in an excavation or material to be used as fill may experience an overall decrease in integrity through freezing induced fracturing, the smaller samples used to determine liquid and plastic limits would more likely reflect the smaller scale changes resulting from desiccation. Freezing induced structural changes via localized desiccation may therefore have a profound effect on soil plasticity values used during project design.

4.1 Role of initial soil structure

Many studies have reported decreases in the liquid limit as a result of cyclic freezing and thawing (e,g., Knutsson, 1984; Aoyama et al., 1985; Yong et al., 1985; Vähäaho, 1988; Swan and Greene, 1998; Swan, et al., 2013). This decrease is commonly associated with the aforementioned desiccation effects and concomitant consolidation via the suction developed during freezing induced pore water migration towards the freezing front. This finding is in general agreement with the data presented here for the unstructured samples, but not for the structured soil. The desiccation and overconsolidation explanation is also consistent with the visual observation of the development of a fabric apparently due to brittle fracture within the unstructured soils.

The definition of "structured" must be considered in this explanation. The originally structured soils in this study represented those sampled from a bare surface, with the existing structure being due to pedalogical processes (e.g., wetting and drying, cyclic freezing and thawing, etc.). Conversely, the unstructured soils were those that underwent complete dispersion and subsequent drying. The structural state of these samples would be much more consistent with undisturbed samples taken from depth and thus more similar to those used in the aforementioned studies that observed decreased liquid limits following cyclic freezing and thawing. The initial extent of inter-particle bonding has been cited as both an important control in the effect of the freezing process (e.g., Eigenbrod, 1996) and the most likely soil property affected by it (e.g., Yong et al., 1985; Qi et al, 2006). The less dense nature of the naturally structured soils may have therefore experienced an increase in liquid limit as the freezing process caused a densification of the natural soil aggregates through increased effective stress, thus increasing the extent of the inter-particle bonding. Conversely, the more massive fabric of the dispersed and dried unstructured samples may have experienced decreasing liquid limits as densification of the soil mass on a larger scale tended towards a granular fabric more consistent with that of the originally structured soils.

It is important to reiterate, however, that the noted increases in both the liquid and plastic limits of the originally structured soils, and decreases in the liquid and plastic limits for the unstructured samples, with an increasing number of freezing and thawing cycles were not statistically significant. This lack of significance may be interpreted as no effect of cyclic freezing and thawing on either the liquid or plastic limits of either the structured or unstructured soils. If so, this suggests that any freezing induced desiccation did not have the effect of changing either the liquid or plastic limits in either the naturally structured or unstructured soils.

Further consideration must also be given to the factor of time frozen. The very low hydraulic conductivity of clay rich soil naturally restricts the flow of water towards the freezing front. That the unstructured samples showed a decrease in liquid limit (although not statistically significant) and a visually apparent fabric development suggests that increased effective stress and desiccation through pore water movement did occur during freezing. This begs the question of whether much longer time periods in the frozen state than the 6 hours of this study would intensify the desiccation effect to the point of resulting in a statistically significant effect.

4.2 Role of clay content

The general relationship of higher liquid and plastic limits with higher clay contents was generally found. Although there were several minor exceptions with the higher clay content soils, the lowest clay content soil consistently exhibited the lowest liquid and plastic limits. More noteworthy was the equality of the slopes of the of both the liquid and plastic limits versus the number of freezing and thawing cycles suggesting a similar, although non-significant effect, of freezing and thawing regardless of clay content. The clay content of the soil controls only the magnitude of the effect rather than the rate of change with cyclic freezing and thawing.

Although plasticity is attributed to inherent properties of the clay fraction of the soil, the distinction between clay minerals and clay sized material is not often made. Although apparent in the grain size distribution as clay, the behaviour of clay sized particles would not likely be the same as actual clay minerals (Seed et al., 1964).

It has been suggested that the finer the soil and the greater the surface area, the greater the liquid limit as it relates to the interaction between fine soil particles and the surrounding pore water (Seed et al., 1964). There is some suggestion in the literature that cyclic freezing and thawing may result in changes in the actual grain size distribution resulting from particle fracturing (Claridge, 1965; Lincoln and Tettenhorst, 1971; Leshchikov and Ryashchenko, 1973; Leporskiy et al, 1990; Konishchev and Rogov, 1993; Qi et al., 2006). Thus, if cyclic freezing and thawing resulted in the comminution of clay sized particles, one would expect to see a corresponding increase in the liquid limit. It would be expected that if this process were occurring, it would be consistent across both structural cases. In all cases, however, any changes in the liquid limit with freeze-thaw cycling were not statistically significant.

The distinction between clay sized material and clay minerals would also play a role in the nature and extent of freezing induced structural changes. In clay sized material the rearrangement of grains forming the skeleton of the soil controls structural change. In clay minerals, however, both inter- and intra-particle effects, including the hydration state of the diffuse double layer between clay plates, must be considered. Several authors attribute the liquid limit to the intensity of the net attractive force between individual clay mineral particles, e.g., effective stress (Seed et al., 1964; Yong et al., 1982) which can be increased upon freezing induced desiccation and the concomitant structural changes (Norrish and Rausell-Colom, 1962; Sangrey et al., 1976; Saunders et al., 1986; Leroueil et al., 1991; Swan and Greene, 1998; Hohmann-Porebska, 2002). Kozlowski (2009) similarly suggests the plastic limit is strongly associated with the phase change upon freezing. Swan et al. (2013) found a small drop in the plastic limit after freezing and thawing but Knutsson (1984) and Roy et al. (1995) found the plastic limit remained somewhat constant. Whether the plastic limit is susceptible to freezing processes is questionable as at these lower water contents the water is very tightly held within inter-clay plate spaces and may remain essentially unfreezable (Seed et al., 1964). The reversibility of freezing induced plasticity changes is also contested. Some suggest rehydration upon thawing at least partially re-establishes the desiccated diffuse double layer (e.g., Norrish and Rausell-Colom, 1962; Pardini et al., 1995), while others suggests such changes are not reversible (e.g., Sangrey et al., 1976; Yong et al., 1985). Any freezing induced desiccation effects on either clay sized material or clay minerals were not noted as the slopes of the regression lines for both the liquid and plastic limits versus the number of freeze-thaw cycles were not significantly different from zero.

Specific clay mineralogy has been cited as both a control on the effect of the freezing and thawing process (e.g., McDowall, 1960) and an effect (Claridge, 1965; Leshchikov and Ryashchenko, 1973; Boyer, 1975; Vogt and Larqué, 1998) although Yong et al. (1985) suggest it plays less of a role than natural cementing agents in the soil. Clay mineralogy and cementation effects were minimized by sampling from the same geomorphological setting. For all soils vermiculite was the dominant clay mineral and organic matter content was similar.

5 CONCLUSIONS

The liquid limit defines the water content where a soil's behaviour under stress transitions from a plastic state to a viscous liquid and is therefore indicative of the consistency of the soil as primarily dictated by clay content (Swan et al., 2013). The plastic limit, the water content where a soil transitions from a semi-solid to a plastic state, reflects other properties including the specific surface area and microstructure, as well as its correlation with various civil and geotechnical engineering properties including compaction characteristics (Kozlowski, 2009). Alteration of either of these fundamental properties through environmental effects could have profound implications regarding design considerations in fine grained soils.

Although previous research has suggested these properties may be altered including cyclic freezing and thawing, rigorous statistical analysis failed to confirm any of these findings. Naturally structured soils displayed increasing liquid and plastic limits with an increasing number of freeze-thaw cycles while unstructured soils showed the opposite trends, but neither of these were found to be statistically significant relationships. Liquid and plastic limits were generally found to increase with soils with higher clay contents.

These findings suggest that cyclic freezing and thawing and the associated desiccation does not alter the soil matrix to the extent that changes occur in soil plasticity as measured by the Atterberg liquid and plastic limits. Further investigation into the effect of length of time frozen during which freezing induced water migration and concomitant desiccation and consolidation can occur is warranted.

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