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RÉSUMÉ

On trouve dans la partie nord de l'ancien lac glaciaire Agassiz des sols gelés laminés, constitués de couches alternées horizontales d'argile brun sombre et de limon brun clair, entre lesquelles sont intercalées des lentilles de glace. Des essais conduits en laboratoire ont confirmé les résultats des essais in situ avec ancrages au sol, pénétromètres et capsules manométriques à Thompson, au Manitoba. Ces essais avaient démontré que les sols présentaient une meilleure résistance mécanique dans le sens horizontal, parallèlement aux couches, que dans le sens vertical. On a échantillonné des blocs non perturbés de ces sols gelés laminés (à varves), et préparé des éprouvettes, orientées de façons diverses par rapport à la direction de la stratification. Des essais de résistance à la compression sans étreinte latérale, effectués sur des échantillons naturellement gelés, et sur d'autres remaniés et artificiellement gelés, ont démontré l'importante anisotropie de la résistance mécanique due à l'anisotropie naturelle de la structure du sol.

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UNCONFINED COMPRESSION TESTS ON ANISOTROPIC FROZEN SOILS FROM THOMPSON, MANITOBA

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Laminated frozen soils, consisting of alternate horizontal layers of dark brown clay and light brown silt, with ice lenses between the layers, are found in the northern area of ancient glacial Lake Agassiz. Laboratory tests confirmed the results of in situ ground anchor, penetrometer, and pressuremeter tests performed at Thompson, Manitoba, which showed these soils to be stronger in the horizontal direction, parallel to the layers, than in the vertical direction. Undisturbed block samples of these laminated (varved) frozen soils were obtained and test specimens were prepared at various orientations to the direction of layering. Unconfined compression tests, using both naturally frozen and remolded frozen specimens, have shown the extent of strength anisotropy due to the natural anisotropic soil structure.

INTRODUCTION

A series of in situ creep loading tests was undertaken in the frozen varved clay soils at Thompson, Manitoba, between 1967 and 1974. These field tests included circular plate anchors (Ladanyi and Johnston 1974), power-installed screw anchors (Johnston and Ladanyi 1974), pressuremeter (Ladanyi and Johnston 1973) and electric penetrometer tests (Ladanyi 1976, 1982). Creep equations were developed using the theory of an expanding spherical cavity. It was found that the creep exponent deduced from the static penetration tests was much higher than that found in the pressuremeter tests. Still higher values were obtained from creep tests on the ground anchors, performed earlier at the same site. Since the anchor and penetrometer tests loaded the soil in a vertical direction and the pressuremeter loaded the soil in a horizontal direction, this indicated that the frozen varved clay was more resistant to deformation (i.e., stronger) in the horizontal direction than in the vertical direction. This was attributed to the natural anisotropic structure of the frozen varved soils (Ladanyi 1976). A systematic study was undertaken to determine the influence of the anisotropic structure of these soils on the response to the various loading conditions described above. This paper describes a series of unconfined compression laboratory tests on field samples of frozen varved clay from the Thompson area.

INVESTIGATING STRENGTH ANISOTROPY

The term strength anisotropy is used exclusively in this paper to describe the variation of stress-strain behavior in the soil with direction of loading. Most soils exhibit stress-strain anisotropy, due mainly to the nature of the depositional process. This anisotropy becomes marked in layered or laminated (varved) soils formed by cyclic sedimentation and subsequent one-dimensional consolidation. The testing of unfrozen varved soils to determine their strength and deformation properties has been reported by several authors, including Tschebotarioff and Bayliss (1948), Eden (1955), and Metcalf and Townsend (1960). These investigators performed unconfined compression tests at various orientations to the varves and found a distinct anisotropy in shear strength. In testing Lake Agassiz varved clays from Steep Rock, Ontario, Eden (1955) found that when clay layers predominated, the shear strength was higher when the direction of loading was parallel to the layers. When silt layers predominated, the shear strength was higher when the direction of loading was perpendicular to the layers.

Frozen fine-grained soils often have an anisotropic structure, due to the existence of ice lenses formed perpendicular to the direction of freezing. Livingston (1956) studied the strength anisotropy by performing unconfined compression tests on frozen Keweenaw silt at various orientations to the ice lenses. There was a large scatter among the observed stress and strain values, due to specimen variability and to the extreme sensitivity of the soil-ice mixture to slight variations in temperature at the time of the test, particularly in the temperature range (-1 to -2°C) at which the tests were conducted. These tests indicated that the shear strength was generally higher for specimens with ice lenses parallel to the direction of loading.

The strength anisotropy of soils is usually expressed as the ratio of the shear strength with the major principal stress oriented at various angles to the vertical (S_θ) to the shear strength in the vertical direction (S_0). The obvious angles of significance for horizontally layered soils are $\theta = 45°$, where the maximum shear stress is parallel to the layers, and $\theta = 90°$, where the major stress is parallel to the layers.

The shear strength ratios for the Steep Rock varved clay and frozen Keweenaw silt are shown in Table 1. These ratios indicate a definite strength anisotropy which is dependent upon the properties of the individual layers. It was thought that the frozen varved clay from the Thompson area would show an even greater strength anisotropy than the soils mentioned above, due to the combined presence of horizontal varves and ice lenses.

TABLE 1 Strength Anisotropy of Some Soils From the Literature

Soil	$\frac{S_{90}}{S_0}$	$\frac{S_{45}}{S_0}$	Reference
Lake Agassiz varved clay (Steep Rock, Ontario)			Eden (1955)
predominantly clay layers	1.18	0.51	
predominantly silt layers	0.57	0.92	
Frozen Keweenaw silt	1.23	0.63	Livingston (1956)

SITE LOCATION AND DESCRIPTION

The city of Thompson (55°45'N, 97°50'W) is located in northern Manitoba about 640 km north of Winnipeg, within the discontinuous permafrost zone. Perennially frozen ground occurs in scattered small patches or islands varying in size from a few square metres to several hectares (Johnston et al 1963).

Thompson is also located within the northern extremity of ancient Lake Agassiz, which existed during the Wisconsin period of glaciation (Figure 1). Characteristic of the depositional processes associated with glacial Lake Agassiz was the formation of extensive deposits of laminated (varved) silt and clay. The varved soils are fully saturated and often contain ice lenses from hairline to 5-10 cm in thickness, normally oriented parallel to the predominantly horizontal laminations. The alternating horizontal layers of light brown silt and dark brown clay combine with the horizontal ice lenses to produce an anisotropic soil structure.

FIELD PROGRAM

Sampling

A backhoe was used to excavate a test pit to a depth of about 3 m at a site approximately 5.5 km north of the city of Thompson, near the southwest corner of the Thompson airstrip, in March 1978. The pit was located in a large spruce island close to a ground temperature cable installed by the Geological Survey of Canada (GSC) in 1973. The site (GSC 2A) is described in detail by Klassen (1976). The walls of the pit were visually logged, and samples were obtained for water content, organic content and grain size analyses. A log of the test pit is shown in Figure 2.

A layer of distinctly laminated (varved) frozen clay occurred between the depths of 1.25 and 2.25 m. Small (0.3 m^3) blocks of the frozen varved material were wrapped in polyethylene sheeting, placed in insulated boxes packed with ice, and shipped to Ottawa by air. These samples were maintained at -6°C in a cold room until specimens were prepared for testing.

Ground Temperatures

Ground temperatures were measured weekly by NRC staff on the thermistor cable installed at the site by the Geological Survey of Canada. Figure 3 shows ground temperatures obtained in early March 1978 and the maximum, minimum, and mean temperatures for that year. The maximum and minimum temperatures for 1978 were near the extreme values observed for the years 1975-1978. The mean annual ground temperature, at the depth at which the block samples were obtained, was between -1 and -2°C. At the time of sampling, the ground temperature, in the sampling zone, was between -2 and -3°C.

LABORATORY TESTING

Test Specimen Preparation and Description

Cylindrical test specimens 76 mm in diameter and 152 mm in height were machined from the block samples using a band saw and lathe in a cold room. The procedures for sawing, machining and preparing the specimens are described by Baker (1976). Specimens were machined at various angles to the plane of the horizontal varves. "Vertical" specimens contained varves oriented perpendicular to the vertical axis of the specimen. "Horizontal" specimens contained varves oriented parallel to the vertical axis of the specimen. Another set of specimens was machined with varves oriented at 45° to the vertical axis of the specimen. Each specimen contained from 15 to 20 varves, consisting of dark brown clay layers from 8 to 12 mm in thickness and light brown silt layers from 2 to 5 mm in thickness. Ice lenses visible on the sides of the specimens ranged in thickness from hairline to a few millimetres.

Bulk densities were determined prior to testing by measuring the volume and weight of the test specimens. After testing they were weighed, oven dried, and weighed again to determine their total water contents. The densities and water contents are presented in Table 2.

Hydrometer tests on "combined" samples (containing both light and dark layers) indicated that the varved soil consisted of 80-90% clay size (<0.002 mm) material. Ignition-loss tests (ASTM D 2974) indicated an average organic content of 12%. Eight Atterberg Limits tests showed a liquid limit of 52.0%, a plastic limit of 32.7%, and a plasticity index of 19.3%. The average water content was 35.0%, about 2-3% lower than that determined at the field site (Figure 2).

Several remolded specimens were specially prepared in the laboratory to try and remove the anisotropic structure formed by the varves and ice lenses. Some specimens were completely thawed, and the soil was mixed and remolded to densities and water contents similar to the natural samples. These remolded cylindrical specimens were placed in the cold room at -6°C and allowed to freeze from all sides. They were removed from the molds, and their ends were machined prior to testing. Small hairline radial ice lenses could be seen at the ends of the frozen remolded specimens. These remolded specimens were tested for comparison with results obtained on the natural (undisturbed) frozen soils. Frozen bulk

TABLE 2 Properties of Test Specimens

Specimen	Bulk density (kg/m^3)	Dry density (kg/m^3)	Water content (% dry wt.)	Loading direction to plane of varves
Undisturbed				
CS-1	1,799	1,332	35.1	Parallel
CS-2	1,791	1,353	32.4	Parallel
CS-3	1,780	1,334	33.5	90°
CS-4	1,766	1,316	34.2	90°
CS-5	1,761	1,284	37.2	90°
CS-6	1,751	1,298	34.9	Parallel
CS-7	1,769	1,288	37.3	45°
CS-8	1,772	1,318	34.4	45°
CS-9	1,759	1,303	35.0	45°
CS-10	1,828	1,374	33.1	Parallel
Mean	1,778	1,320	34.7	
Stand. Dev.	23	29	1.6	
Remolded				
RS-1	1,776	1,340	32.6	
RS-2	1,852	1,440	28.6	
RS-3	1,761	1,303	35.1	
RS-5	1,768	1,303	35.7	
Mean	1,789	1,347	33.0	
Stand. Dev.	42	65	3.2	

densities and total water contents were determined before and after testing; these are presented in Table 2.

Unconfined Compression Tests

Unconfined compression tests were performed at a cold room temperature of -6°C, using a 250 kN capacity screw-driven universal testing machine. These tests were carried out at nominal strain rates of 0.01 and 1.0%/min. Some tests were performed at an intermediate strain rate of 0.1%/min, but were incomplete due to the limited amount of sample material available. Data from this incomplete test series will not be presented. An extensometer consisting of three displacement transducers located on the specimen, measured axial deformation and tilting (Baker et al 1982). Compliant platens (Baker 1978) were used to reduce end effects and to ensure a uniform normal application of pressure to the specimen ends.

Vertically oriented specimens had the maximum normal stress direction perpendicular to the plane of the varves to simulate the anchor and penetrometer tests performed in the field. Horizontally oriented specimens had the maximum normal stress direction parallel to the plane of the varves, in a manner similar to the field pressuremeter tests. Specimens oriented at 45° had the maximum shearing stress directed parallel to the plane of the varves.

Stress-strain curves for the two nominal strain rates are shown in Figures 4 and 5. The loading direction relative to the plane of the varves for each specimen is indicated. Some tests were duplicated to show the variation in stress-strain behavior between specimens. The maximum axial strain imposed on specimens was between 10 and 15%, due to the limitations imposed by the 83 mm diameter extensometer ring. As a result, none of the tests reached peak stress.

DISCUSSION AND CONCLUSION

All of the specimens exhibited an initial yield at about 0.15% axial strain; the stress then continued to increase until the test was stopped. Although none of the specimens reached failure (peak stress), the value of the stresses at and beyond yield is an indicator of the relative strength of specimens and can be used to determine strength anisotropy. All specimens deformed as right cylinders without central bulging or expansion of individual layers. This indicated that the strains within the specimen were uniformly distributed.

In both ranges of strain rate the horizontally oriented specimens were consistently the strongest, followed by the specimens oriented at 45°. The vertically oriented specimens were the weakest. This relationship was also observed in the limited tests performed at the intermediate strain rate. Strength increase with strain rate seemed to be similar for all specimen orientations. Tests that were duplicated showed very similar stress-strain behavior. This probably reflects the narrow range in the natural physical properties (densities and total water content). The similarities in physical properties between specimens enhanced the reliability of comparing the test results. The remolded laboratory-frozen specimens were as much as 80% stronger than the naturally-frozen undisturbed specimens. Although there was some anisotropy in the structure of the remolded specimens, these results indicated that the natural anisotropic structure acts to reduce the shear strength.

The strength anisotropy is shown in Table 3 for the two strain rates and for axial strains corresponding to yield (0.15%) and 10%. The amount of anisotropy is not pronounced at yield or at small strain rates, but it becomes quite significant at 10% strain. High horizontal strengths are similar

TABLE 3 Strength Anisotropy

Axial strain (%)	Nominal strain rate (%/min)	$\frac{S_{90}}{S_0}$	$\frac{S_{45}}{S_0}$	$\frac{S_0}{S_R}$
0.15 (yield)	0.01	0.93	0.99	0.55
	1.0	1.14	1.18	0.67
10.0	0.01	1.13	1.03	0.72
	1.0	1.35	1.06	0.83

to those observed by Eden (1955) in unfrozen varved clays from Steep Rock when the clay layers predominated. Specimens in this study had a high clay content (80-90%). High shear strengths at 45° orientations have not been seen in any of the data on varved soils in the literature. Ice cementation may resist the shearing stresses acting between the layers. The higher strain rates used in this study are comparable to those used by Eden (1955) and Livingston (1956) in their test programs. Frozen Thompson varved clays appear to exhibit a greater strength anisotropy than either the unfrozen varved clay from Steep Rock (Eden 1955) or the frozen Keweenaw silt (Livingston 1956).

An estimate of the average unfrozen water content of the combined soil at the in situ temperature of -1°C, based on the liquid limits, is 15% (Tice et al. 1976). The unfrozen water content would probably be different in the individual clay and silt layers, due to the surface area of the soil grains, and would influence the relative stress-strain behavior of these layers. It is recognized that the change from the in situ temperature to the laboratory temperature of -6°C, coupled with sublimation of the samples during 2 years of cold storage, would lower the unfrozen water content. The strength anisotropy in these specimens is probably due to the combined effect of the varves and their different unfrozen water contents, and other physical properties, as well as to the ice lenses. No attempt was made to estimate the relative contribution of these various components.

The series of in situ tests performed by Johnston and Ladanyi in an attempt to determine the bearing capacity of the frozen varved soils at Thompson were analyzed using cavity expansion theory to estimate the stress-strain behavior of the soil. Cavity expansion theory assumes that the soil behaves as a homogeneous, isotropic, ideally plastic material (Ladanyi 1963). Horizontal varves and ice lenses make these soils heterogeneous. This laboratory study has shown that these soils are not isotropic but anisotropic in their stress-strain behavior. The stress-strain curves indicate that these soils do not deform in an ideally plastic manner. A modification could be made to the cavity expansion theory to take into consideration strength anisotropy. Davis and Christian (1971) have proposed a modification, taking into consideration strength anisotropy, to the yield criterion which Scott (1963) recommended for predicting the bearing capacity of undrained soils. They show strength anisotropy to be present in most cohesive soils.

A more detailed laboratory study similar to the one presented in this paper would be needed to determine the complete range and magnitude of strength anisotropy associated with a particular soil deposit. One would have to consider the influences of various components of the soil deposit (number and physical properties of the varves, ice lenses, etc.) that could contribute to the anisotropy. The results of field testing using the pressuremeter and penetrometer would provide a useful check on the strength relationships obtained and a qualitative appraisal of the influences of sampling and testing procedures.

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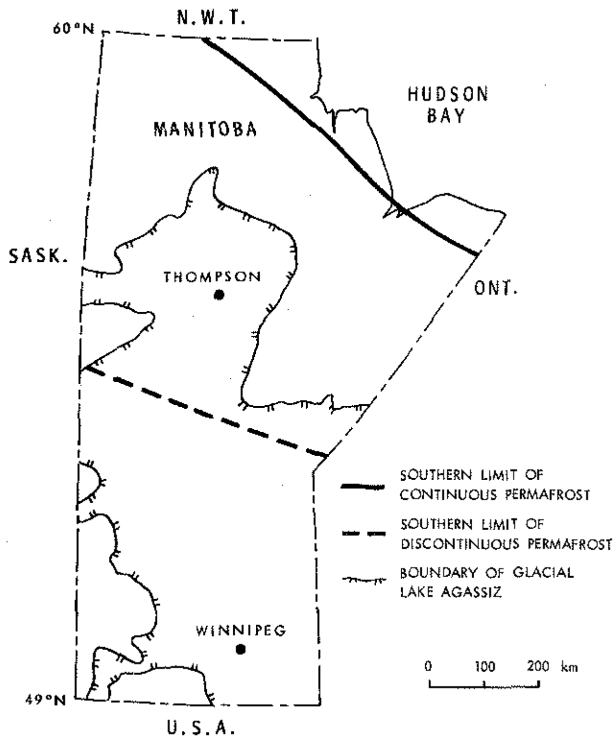

FIGURE 1 Location map.

SOIL DESCRIPTION	SOIL PHASE	ICE PHASE
Living moss, Peat	Pt	None
Dark brown frozen peat	Pt	Nbe
Light brown frozen clay silt (not laminated)	CL	Vr
Frozen varved clay light brown silt layers (1/2 - 2 cm) dark brown clay layers (2 - 6 cm), ice lenses (2 - 4 cm)	CL	Vs
Light brown frozen clay silt, plastic frozen (not laminated)	CL	Nbe

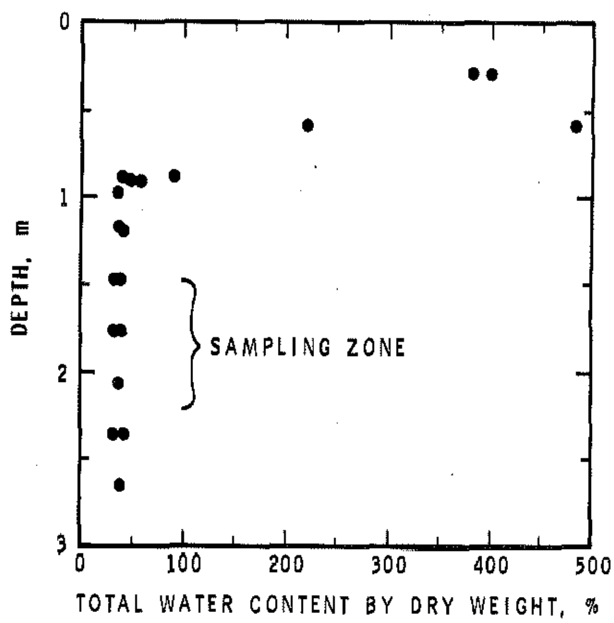

FIGURE 2 Log of test pit.

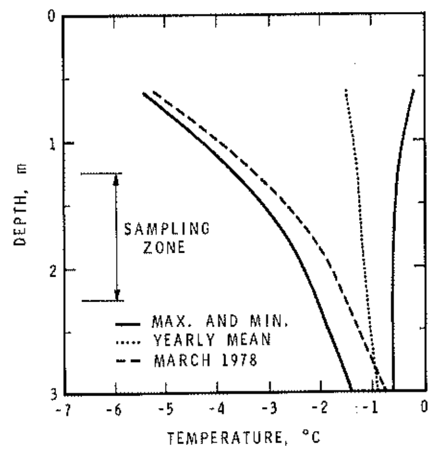

FIGURE 3 Ground temperatures, from temperature cable. GSC site 2A, Thompson, Manitoba.

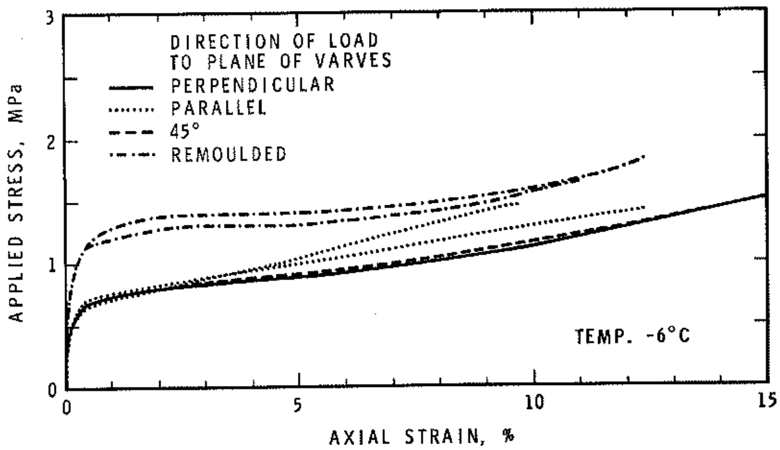

FIGURE 4 Stress-strain curves at 0.01%/min.

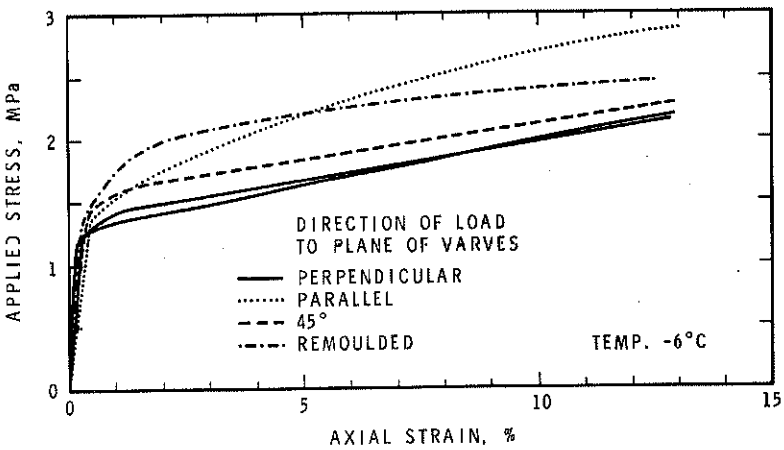

FIGURE 5 Stress-strain curves at 1.0%/min.