Acoustic and mechanical properties of frozen sand

Baker, T. H. W.; Kurfurst, P. J.

Publisher's version / Version de l'éditeur:

Ground Freezing: Proceedings of the 4th Internaitonal Symposium on Ground Freezing, 1, pp. 227-234, 1985

National Research Council Canada
Conseil national de recherches Canada

Division of Building Research
Division des recherches en bâtiment

Acoustic and Mechanical Properties of Frozen Sand

by T.H.W. Baker and P.J. Kurfurst

Reprinted from
Proceedings of the Fourth International Symposium on Ground Freezing
Sapporo, Japan. August 5-7, 1985
Volume 1, p. 227-234
(DBR Paper No. 1338)

Price $2.50

NRCC 25200

DBR/DRB

Canada

RÉSUMÉ

Il existe une dépendance entre d'une part la vitesse de propagation des ondes longitudinales à -10 et -3,2°C et la résistance à la compression sans étreinte latérale, et, d'autre part, la densité sèche d'échantillons de sable saturé d'eau douce et gelé dans la gamme de densités 1 550 - 1 780 kg/m^3. La vitesse de propagation des ondes transversales est indépendante de la densité sèche aux deux températures mentionnées. La propagation des ondes sonores et la résistance à la compression sans étreinte latérale ne varient pas avec la densité sèche lorsqu'on ajoute du sel à l'eau interstitielle avant le gel. L'accroissement de la salinité réduit grandement la vitesse de propagation des ondes sonores et la résistance. Cette réduction est particulièrement sensible lorsque la salinité se situe entre 0 et 5 ppt. On a comparé les constantes élastiques ultrasoniques à la densité sèche et à la salinité. Il faudrait effectuer des essais de mesure de la densité sèche et de la salinité lors des études techniques portant sur la congélation du sol et sur la construction dans les sols gelés, et utiliser des mesures acoustiques pour déterminer les constantes élastiques des sols gelés employées dans la modélisation numérique.

Fourth International Symposium on Ground Freezing / Sapporo / 5-7 August 1985

Acoustic and mechanical properties of frozen sand

T.H.W.BAKER
National Research Council Canada, Ottawa

P.J.KURFURST
Geological Survey of Canada, Ottawa

ABSTRACT: Compressional wave velocities at -10.0 and -3.2°C and the unconfined compressive strength show a dependency on the dry density of frozen freshwater sand specimens in the density range 1550 to 1780 kg/m^3. Shear wave velocities are independent of dry density at both temperature levels. Acoustic wave velocities and unconfined compressive strength are independent of dry density when salt is added to the pore water prior to freezing. Increasing the salinity greatly reduces acoustic wave velocities and strength. These reductions are most pronounced when the salinity is between 0 and 5 ppt. Ultrasonic elastic constants were compared with dry density and salinity. Dry density and salinity tests should be included in engineering site investigations related to artificial ground freezing and frozen ground construction and acoustic measurements should be used to determine the elastic constants of frozen soils used in numerical modelling.

1 INTRODUCTION

Acoustic wave propagation and mechanical strength tests are important laboratory techniques for engineering investigations of soils and rocks. This paper compares results of such tests on frozen sand and describes the effects of specimen dry density and salinity on the measurement of unconfined compressive strength, shear and compressional wave velocities and the calculation of Young's modulus, Poisson's ratio, shear modulus and bulk modulus. These properties are used in finite element analyses and other numerical modelling techniques employed in the design of artificially frozen soil structures and geological engineering investigations in frozen ground.

2 TESTING PROCEDURES AND EQUIPMENT

Sample preparation followed the methods described by Baker and Konrad (1985). Three sets of samples were prepared at various dry densities ranging from 1550 to 1780 kg/m^3 and were saturated with de-aired, distilled water. These samples are referred to in this paper as freshwater samples. Two more sets of samples were prepared, one at a density of 1550 kg/m^3 (low density samples) and the other at a density of 1780 kg/m^3 (high density samples). These samples were saturated with sea salt solutions ranging from 0.5 to 40 ppt. All samples were frozen unidirectionally in a cold room at -10.0°C and then were prepared by machining and end facing on a bandsaw and lathe. Some specimens heaved during the freezing process and were discarded. The final specimens were cylinders approx. 76 mm in diameter and 150 mm in height.

All machined frozen specimens were stored at -10.0°C, but were transferred to -3.2°C for about 24 hours for acoustic velocity testing. The specimens were then returned to -10.0°C prior to the mechanical tests. Temperature measurements indicated that frozen specimens required about 12 hours to adjust to these temperature changes. Specimens with pore water salinities greater than 10 ppt crumbled when warmed to -3.2°C and replacement specimens were made at 20 and 30 ppt for the mechanical strength testing.

2.1 Acoustic Tests

The acoustic wave propagation measurements were made on one set of freshwater specimens and on all of the saline water specimens. These measurements were made at -10.0 and -3.2°C using an OYO 5217-A, Sonic-viewer. Details of the measuring technique and equipment have been described elsewhere by King, (1970) and Kurfurst and King (1972).

The compressional (V_p) and shear wave (V_s) velocities were calculated as follows:

$$V_p = L_p/T_p, \text{ and} \tag{1}$$

$$V_s = L_s/T_s \tag{2}$$

where V = pulse propagation velocity (m/s),
L = pulse travel distance (m),
T = effective pulse-travel time (s).

Ultrasonic elastic constants (E, μ, G, K) were calculated using formulas recommended by the American Society for Testing and Materials, Standard D2845-83 (ASTM, 1984):

$$E = \left[\rho\ V_s^2\ (3\ V_p^2 - 4\ V_s^2)\right] / (V_p^2 - V_s^2) \tag{3}$$

where E = Young's modulus of elasticity (Pa),
ρ = density (kg/m^3);

$$\mu = (V_p^2 - 2\ V_s^2)/[2\ (V_p^2 - V_s^2)] \tag{4}$$

where μ = Poisson's ratio;

$$G = \rho\ V_s^2 \tag{5}$$

where G = shear modulus (or modulus of rigidity) (Pa);

$$K = \rho\ (3\ V_p^2 - 4\ V_s^2)/3 \tag{6}$$

where K = bulk modulus (Pa).

2.2 Mechanical Strength Tests

Unconfined compression tests were performed on one set of freshwater specimens and on all saline water specimens at -10.0°C, using a screw-driven testing machine (Instron Model 1127, 250 kN load capacity frame). Testing procedures closely followed the guidelines proposed by the International Working Group on Testing Methods for Frozen Soils (Baker et al 1985). The tests were performed at a nominal strain rate of 1.67×10^{-4} s^{-1} (1% min^{-1}). The details of equipment used are described in Baker et al (1981).

A second set of freshwater test specimens was tested using a closed-loop, servo-hydraulic testing machine (MTS Model 810.15, 1.0 MN load capacity frame and a 250 kN capacity actuator). The strain rate was controlled during the test at 1.67×10^{-4} s^{-1} (1% min^{-1}) using a control gauge mounted on the test specimens.

The third set of freshwater test specimens was tested in the closed-loop, servo-hydraulic testing machine to determine the elastic modulus during rapid unloading. The specimens were loaded in compression, at a constant strain rate of 1.67×10^{-4} s^{-1}, up to a stress of 4 MPa and then rapidly (0.3 to 0.4 s) unloaded. The rebound of each specimen was recorded and the initial rapid (0.15 s) displacement was used to calculate the unloading modulus (E_u). When the displacement stopped, the specimen was again subjected to loads of 5 and 6 MPa and unloaded at each stress level. In this way, three determinations of the elastic unloading modulus were made on each specimen.

3 TEST RESULTS

3.1 Acoustic Tests

The results of the acoustic wave propagation tests on the freshwater specimens are shown in Figures 1 to 3. An increase in temperature from -10.0 to -3.2°C resulted in a small increase in compressional wave velocity; however the changes in the shear wave velocity were within the error of the test method. The change in compressional velocity may be due to the very small changes in unfrozen water content between these two temperatures or to other characteristics of the ice matrix.

When the dry density was increased from 1550 to 1780 kg/m^3, the acoustic wave velocities and elastic constants increased with increasing dry density of sand. The shear wave velocity is relatively independent of dry density over the density and temperature ranges measured. The compressional wave velocity is more dependent on dry density at -10.0°C than at -3.2°C. An anomaly in the acoustic data exists at a density of about 1630 kg/m^3. This was attributed to ice lenses in the specimen.

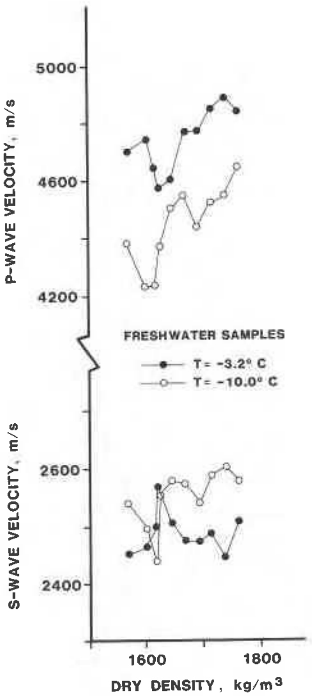

Fig. 1. Effect of changing dry density on acoustic velocities

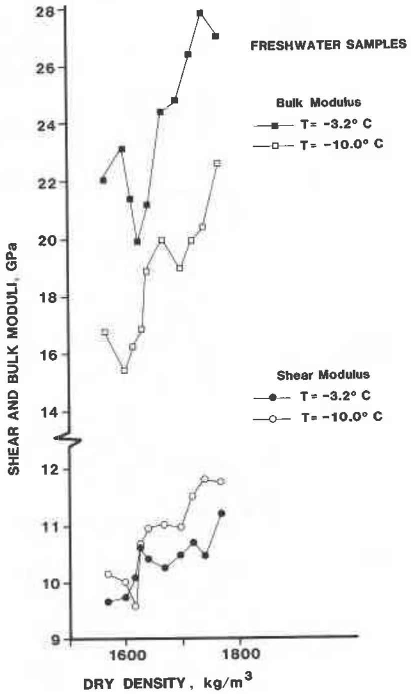

Fig. 3. Effect of changing dry density on shear and bulk moduli

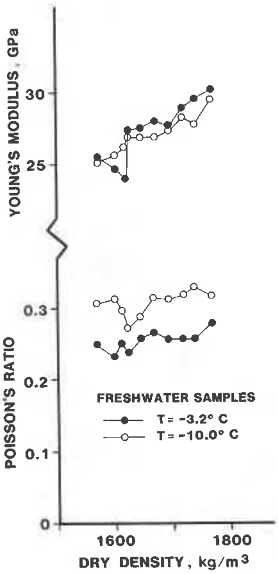

Fig. 2. Effect of changing dry density on Poisson's ratio and Young's modulus

The results of the acoustic wave propagation tests on the saline water specimens are presented in Figures 4 to 8. Specimens with salinities greater than 10 ppt at -3.2°C crumbled under the minimum loads required to secure the acoustic transducers. Some measurements were made on specimens with 20 ppt salinity at -3.2°C; these measurements have been plotted, but their validity is questionable.

Increasing the temperature from -10.0 to -3.2°C resulted in a moderate decrease in compressional wave velocities at salinities up to 5.0 ppt and a very large decrease at higher salinities. Shear wave velocities showed a very large decrease between -10.0 and -3.2°C with increasing salinity over the entire range studied. The temperature effect on both velocities was more pronounced at the higher salinities, corresponding to the larger amounts of unfrozen water present in the soil.

Changes in the unfrozen water content occurring in saline sands when the temperature changed from -10.0 to -3.2°C

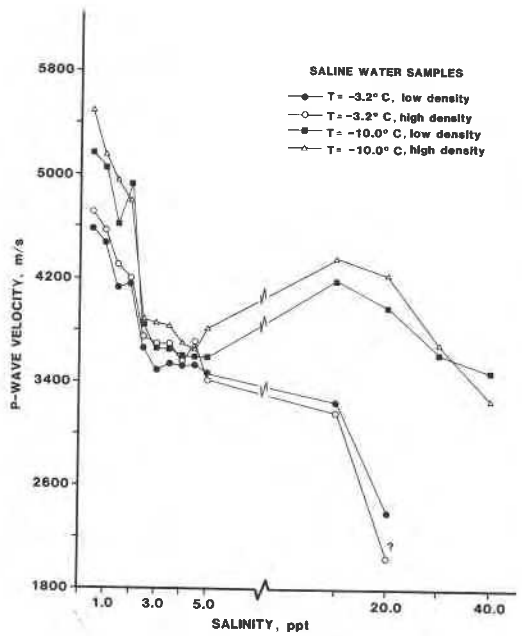

Fig. 4. Effect of changing salinity on compressional wave velocity

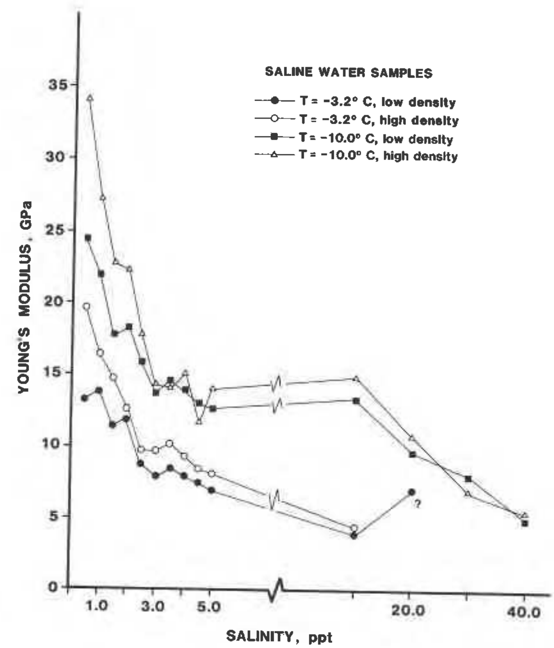

Fig. 6. Effect of changing salinity on Young's modulus

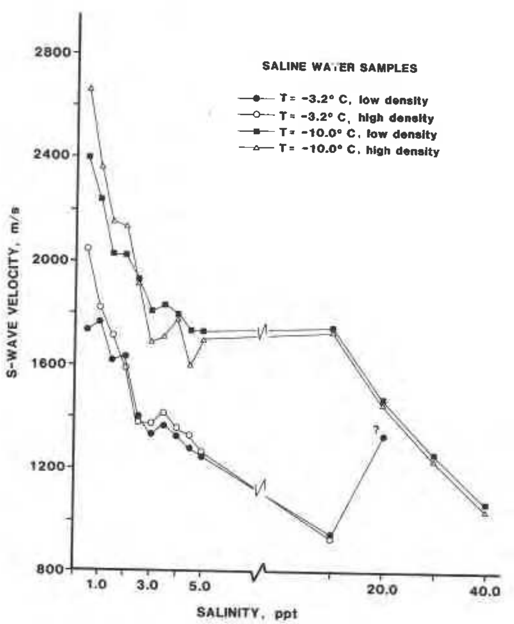

Fig. 5. Effect of changing salinity on shear wave velocity

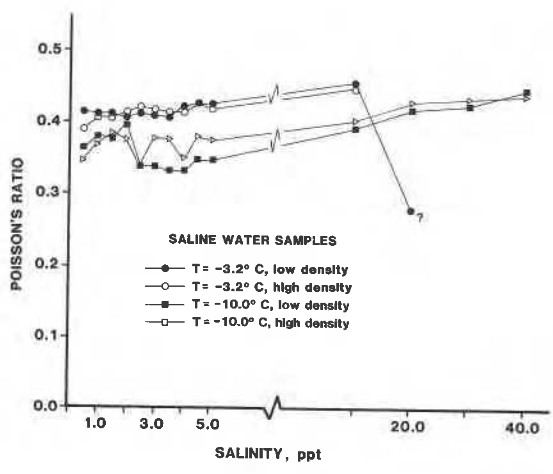

Fig. 7. Effect of changing salinity on Poisson's ratio

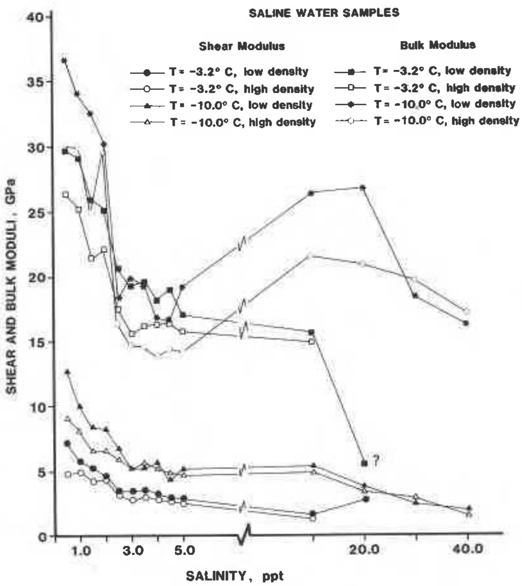

Fig. 8. Effect of changing salinity on shear and bulk moduli

were calculated; the calculations were based on the freezing point depression, due to salt in the pore water, and the specific surface area of the sand particles. Results of these calculations, which must be considered approximate because of the nature of the condition, are presented in Table 1. The ratio of the unfrozen water contents between -10.0 and -3.2°C is compared with the ratio of acoustic wave velocity

Table 1. Effect of changes in the ratio of unfrozen content (W_u) at -10.0 and -3.2°C on the acoustic wave velocities (V_p, V_s)

Pore Water Salinity	Ratio of values at -10.0:-3.2°C		
(ppt)	W_u	V_p	V_s
0.5	1: 400	1:1.14	1:1.32
2.0	1: 600	1:1.05	1:1.39
5.0	1: 700	1:1.07	1:1.36
10.0	1: 1,000	1:1.34	1:1.84
20.0	1: 6,000	-	-
30.0	1:50,000	-	-
40.0	Not frozen at -3.2°C	-	-

measurements. There is an exponential relationship between the ratio of unfrozen water content and salinity that is not reflected in the ratio of acoustic velocity measurements below 5 ppt, but does appear to be similar to changes occurring between 5 and 10 ppt.

The effect of increasing salinity on the acoustic velocities and elastic constants is shown in Figures 4 to 8. Compressional and shear velocities and Young's shear and bulk moduli all exhibit dramatic decreases at salinities up to 5 ppt and, for the most part, level off at higher salinities. Poisson's ratio was approximately constant for all salinity levels. Changes of less than 10% are probably not significant.

The physical mechanisms which affect these measurements are not fully understood. However, it appears that the bond strength between the ice matrix and the sand particles becomes greatly reduced at salinities greater than 5 ppt.

3.2 Mechanical Strength

Results of the unconfined compression tests are presented in Figures 9 and 10. At a strain rate of 1.67×10^{-4} s^{-1} and a temperature of -10.0°C, the unconfined compressive strength of freshwater sand specimens increases only slightly with increase in dry density up to ~1630 kg/m^3. At higher densities, the increase in unconfined compressive strength is significantly greater. This transition is more dramatic in the strain data, as the strain is about constant at low densities but increases sharply at a density of ~1650 kg/m^3. This transition represents a change in the mode of failure from a lower yield type, usually associated with fractures in the ice matrix, to an upper yield type of failure associated with the frictional resistance of the soil particle structure (Sayles and Carbee 1980).

Three elastic moduli were determined using the results of the mechanical loading and unloading tests:

1. the secant modulus (E_i) determined from the initial slope of the stress-strain curve (Jessberger and Ebel 1981);
2. the deformation modulus (E_{50}) determined from the tangent to the stress-strain curve at 50% of the lower yield stress (Japan Gas Association 1979); and
3. the unloading modulus (E_u) determined from the initial slope of the stress-strain curve when the specimen has

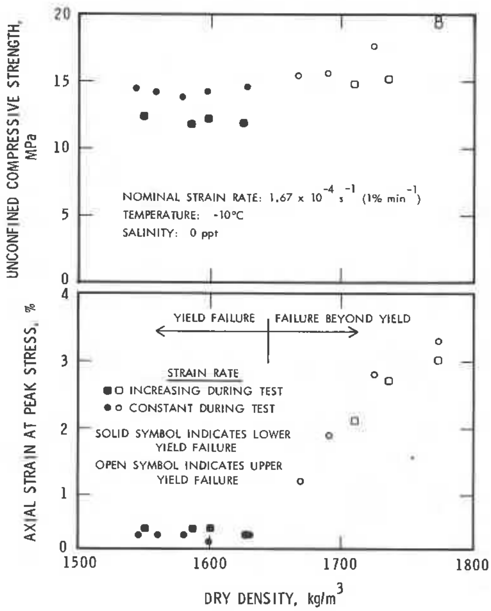

Fig. 9. Effect of changing dry density on unconfined compressive strength and failure strain

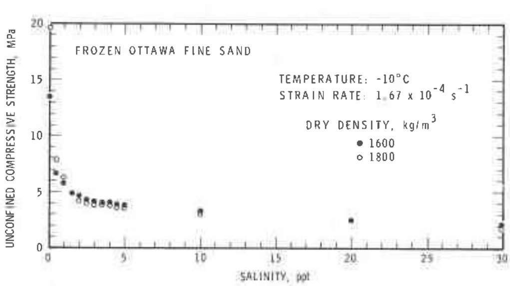

Fig. 10. Effect of changing salinity and dry density on unconfined compressive strength

been immediately unloaded after a small load is applied (Sinha 1982).

The moduli from the mechanical tests on the frozen freshwater specimens are presented in Table 2. The values of the unloading modulus represent the average of three values obtained for each specimen. Although there is not a consistent trend with increasing density, the most dense specimen had the highest modulus. The values of E_i and E_{50} are comparable to other published data for sandy soils at -10°C (Parameswaran 1980; Japan Gas Association 1979). The low values measured at a density of 1630 kg/m^3 may be related to the presence of ice lenses in the specimen. The unloading modulus E_u was the highest of the moduli. Since it was determined in 0.15 s, it is considered to be the most representative of the elastic behaviour of the specimens. The change in unloading moduli was not consistent with increasing density, but was within the same range of values as determined from the acoustic tests (Figure 2).

Table 2. Elastic moduli from mechanical and acoustic tests

Dry Density kg/m^3	Mechanical Tests E_i GPa	E_{50} GPa	E_u GPa	Acoustic Tests E GPa
1580	14	14	28	25
1600	18	9	27	24
1630	5	6	30	28
1660	36	13	33	28
1690	19	10	26	28
1780	30	30	45	30

The effect of salinity on the unconfined compressive strength at -10.0°C is shown in Figure 10. A small increase of salinity from 0 to 0.5 ppt greatly reduces the compressive strength. The reduction of strength with increased salinity is most significant up to 5 ppt, with more gradual decreases occurring with higher salinities. Changes in dry density of the specimens had very little effect on their strength. The mode of failure was consistently a lower yield type of failure at an axial strain of less than 1%, indicating that the ice matrix was responsible for the observed behaviour. Salt in the specimens increased the unfrozen water content and weakened the contribution of the ice matrix to the compressive strength. The frictional component of strength did not affect the behaviour of any of the frozen saline specimens at a salinity of 0.5 ppt.

4 CONCLUSIONS

The results of the acoustic tests of frozen freshwater specimens show that the compressional wave velocity and the elastic constants increase directly with increasing density at both -10.0 and -3.2°C. However, the shear wave velocity is relatively independent of dry density over the density and temperature ranges measured.

The results of the acoustic tests on frozen saline specimens show that the acoustic measurements are independent of dry density. However, both the acoustic wave velocities and elastic constants decrease directly with increased temperature, especially at salinities between 0.5 and 5 ppt. These changes are associated with the influence of the ice matrix and the bond strength between the ice and sand structures.

The results of the mechanical strength tests indicate that the unconfined compressive strength of frozen freshwater specimens increases with increased dry density, with the rate of increase greater at the higher density range; the strain data show a similar transition. This transition indicates a change in failure mode from a lower yield type of failure, associated with fractures in the ice matrix, to an upper yield type of failure associated with the frictional resistance of soil particle structure.

The loading and unloading moduli determined in this study are similar in value to those documented in the literature. The unloading modulus has the highest value and agrees well with the Young's modulus determined from the acoustic tests.

The unconfined compressive strength at -10.0°C decreases directly with increased pore water salinity. A large reduction in strength occurs from a salinity of 0 to 5 ppt, and decreases more gradually over the range from 5 to 30 ppt. The unconfined compressive strength of saline frozen sands is independent of the dry density.

Measurement of acoustic wave velocity is an inexpensive, nondestructive method for obtaining elastic constants, especially the Young's modulus. These values are often used in time dependent constitutive equations for numerical modelling.

5 RECOMMENDATIONS

Density, salinity and acoustic measurements should be performed on all soil samples obtained from engineering site investigations related to the use of artificially frozen ground as a load bearing structure. Similar measurements should be made on samples obtained during investigations for foundations or other load engineering structures to be supported by naturally frozen soils.

Acoustic wave velocity measurements are easier to perform than mechanical tests for the determination of realistic values of the elastic moduli of frozen soils. Additional tests should be performed to verify if this is also the case for fine-grained soils at various salinities.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the assistance of J.G. Bisson, J.-F. Morel and A. Krol in performing the laboratory tests.

This paper is a joint contribution of the Division of Building Research, National Research Council of Canada, and of the Terrain Sciences Division, Geological Survey of Canada and is published with the approval of the Directors of both Divisions.

REFERENCES

American Society for Testing and Materials, 1984, Standard test method for laboratory determination of pulse velocities and ultrasonic elastic constants of rock. in Annual book of standards, V. 04.08, No. D2845-83, Philadelphia.

Baker, T.H.W. et al., 1985, Guidelines for classification and laboratory testing of artificially frozen ground: Report of the International Working Group on Testing Methods for Frozen Soil. in Proceedings of the Third International Symposium on Ground Freezing, v. 2, Hanover, N.H.

Baker, T.H.W., Jones, S.J. and Parameswaran, V.R., 1981, Confined and unconfined compression tests on frozen sands. in Proceedings of the Fourth Canadian Permafrost Conference (The Roger J.E. Brown memorial volume): Ottawa, National Research Council of Canada.

Baker, T.H.W. and Konrad, J.-M., 1985, Effect of sample preservation on the strength of frozen sand. in Proceedings of the Fourth International Symposium on Ground Freezing, Sapporo: Institute of Low Temperature Science, Hokkaido University.

Japan Gas Association, 1979, Recommended practice for liquified natural gas inground storage. Japan Gas Association Committee on Liquified Natural Gas Storage, Tokyo.

Jessberger, H.L. and Ebel, W., 1981, Proposed method for reference tests on frozen soils: Engineering Geology, v. 18, p. 31-34.

King, M.S., 1970, Static and dynamic moduli of rocks under pressure. in Somerton, W.H., ed., Rock Mechanics, Theory and Practice: New York, N.Y., American Institute of Mechanical Engineering.

Kurfurst, P.J. and King, M.S., 1972, Static and dynamic elastic properties of two sandstones and permafrost temperatures. in Transactions American Society of Mechanical Engineering, v. 253, New York, N.Y.

Parameswaran, V.R., 1980, Deformation behaviour and strength of frozen sand: Canadian Geotechnical Journal, v. 17, p. 74-88.

Sayles, F.H. and Carbee, D.L., 1980, Strength of frozen silt as a function of ice content and dry unit weight. in Proceedings of the Second International Symposium on Ground Freezing, Trondheim: The Norwegian Institute of Technology, Trondheim.

Sinha, N.K., 1982, Delayed elastic strain criterion for first cracks in ice. in Proceedings of the Symposium on Deformation and Failure of Granular Materials, Delft: International Union of Theoretical and Applied Mechanics, Delft.