Compressive strengths and dynamic elastic properties of frozen and unfrozen iron ore from Northern Québec

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Ultrasonic compressional and shear-wave velocities and uniaxial and triaxial compressive strengths have been measured on naturally-occurring permafrost samples of iron ore and on originally unfrozen water-saturated samples of the same formation. Fractional porosities of the iron ore ranged from 0.08 to 0.37, and the water saturation ranged from 0.53 to fully saturated. Tests were conducted in the temperature range −13 to 20°C.

Compressional and shear-wave velocities measured at subzero temperatures on permafrost and originally unfrozen ore are approximately the same, provided the moisture content and porosity are equivalent. The ultrasonic velocities and compressive strength of frozen and thawed iron ore are strongly influenced by the magnitude of porosity and moisture content. The velocities and strength both increase as the porosity decreases or as the moisture content increases. Iron ore frozen is more homogeneous in its elastic properties than when it is thawed.

A correlation was found to exist between the compressive strength of the frozen and unfrozen iron ore and the dynamic elastic modulus calculated from the ultrasonic velocities and density. A linear relationship exists between the compressive strength of frozen and unfrozen iron ore of approximately the same porosity and the compressional-wave velocity squared. It is concluded that seismic surveys may therefore be expected to provide a good estimate of the strength of iron ore frozen and unfrozen.

On a mesuré les vitesses de propagation d'ondes de compression et d'ondes de cisaillement ultrasoniques, ainsi que la résistance à la compression sous l'effet de contraintes uniaxiales et triaxiales, sur des échantillons naturels de minerai de fer recueillis dans le pergélisol et des échantillons initialement non gelés, mais saturés en eau et recueillis dans la même formation ferrifère que les premiers. La porosité fractionnée du minerai de fer se situait entre 0,08 et 0,37, et la saturation de l'eau allait de 0,53 à un degré de saturation totale. On a effectué les essais dans la gamme de températures −13 à 20°C.

Les vitesses des ondes de compression et de cisaillement, mesurées à des températures inférieures à zéro sur du minerai provenant du pergélisol et du minerai initialement non gelé sont à peu près les mêmes, à condition que la teneur en eau et la porosité soient semblables. Les vitesses de propagation des ondes ultrasoniques et la résistance à la compression du minerai gelé et du minerai dégelé sont fortement influencées par le degré de porosité et la teneur en eau. Les vitesses de propagation des ondes et la résistance à la compression augmentent toutes deux lorsque diminue la porosité ou lorsqu'augmente la teneur en eau. Le minerai de fer gelé est plus homogène du point de vue des propriétés élastiques qu'à l'état dégelé.

On a découvert qu'il existait une corrélation entre la résistance à la compression du minerai de fer gelé et dégelé, et le module d'élasticité dynamique calculé d'après les vitesses de propagation des ondes ultrasoniques et la densité. Il existe une relation linéaire entre la résistance à la compression du minerai gelé et du minerai dégelé, lorsqu'ils ont à peu près la même porosité, et le carré de la vitesse des ondes de compression. On en conclut que les levés sismiques devraient en principe donner de bonnes estimations de la résistance mécanique du minerai, à l'état gelé et à l'état dégelé.

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Introduction

Geophysical techniques have been successfully employed for a number of years to delineate permafrost in iron ore open-pit mining operations in northern Québec (Garg 1973, 1977; King and Garg 1980). Benefits accruing from delineating areas of permafrost have been demonstrated to occur in the following areas:

— the economic planning of all stages of mining operations, particularly with respect to production drilling and blasting;
— the identification of zones where free excavation is possible during overburden stripping operations;
— the identification of zones of the pit wall likely to be affected by the presence of permafrost, with consequent slope design and potential groundwater problems; and
— the economic design of blasting patterns and charges to be used in excavating ore.

Garg (1977) has stressed the importance of being able to estimate, for slope stability calculations and the economic design of blasting patterns and charges, the strengths of frozen and unfrozen iron ore. He has suggested that the seismic and electrical resistivity surveys used to delineate areas of permafrost might be employed also to estimate the strengths of the iron ore frozen and unfrozen. The seismic velocities, together with a knowledge of the density, can be used theoretically to calculate the dynamic elastic moduli of the ore. These elastic moduli can be correlated with the strengths, as suggested also by Zykov *et al.* (1978).

The mechanical properties, including the strengths, of three water-saturated rocks frozen and unfrozen have been reported by Mellor (1971). In his discussion, Mellor proposed a theory based on the cementing action of ice formed in the larger pore spaces to explain the dramatic increase in strength observed when a water-saturated porous rock is frozen. The effects of changes in strain rate and temperature on the compressive strength of frozen soils have been described by Ersoy and Togrol (1978) and Haynes (1978). Ersoy and Togrol observed that the effect of strain rate was less significant than a change in temperature on the strength of a compacted frozen silty clay. In contrast, Haynes noted appreciable effects of strain rate on the compressive strength of a silt with a high water content. The effects of strain rate, shape of specimen, and end conditions on the compressive strength of frozen sand have been discussed by Baker (1978), who indicated a relative insensitivity of compressive strength with strain rate. Generally, a higher strength results from a decrease in temperature of a frozen soil, or from an increase in the strain rate in a number of cases.

Results of laboratory measurements of acoustic velocities of rocks and soils at permafrost temperatures have been reported by King (1977), King and Garg (1980), Kurfurst (1976), Kurfurst and King (1972), Nakano and Froula (1973), Nakano *et al.* (1972), Pandit and King (1979), Timur (1968), and Zykov *et al.* (1978). As the temperature was decreased below 0°C, these workers observed increases in the velocities measured, with the degree of increase depending upon the water content and pore size distribution of the porous medium. Kurfurst and King (1972) also reported results of a comparison between static and dynamic elastic moduli for two water-saturated sandstones frozen and unfrozen.

In this paper are reported the results of measurements of ultrasonic compressional and shear-wave velocities and compressive strengths on naturally-occurring permafrost samples of iron ore (Middle Iron Formation) from the Schefferville area of northern Québec, and on artificially frozen and unfrozen water-saturated samples of iron ore obtained from the same formation as the permafrost samples. Details of the setting of a typical open-pit iron ore mine in the Schefferville area are provided by Garg and Devon (1978). Naturally-occurring permafrost was shipped in blocks tightly wrapped in plastic film, with the temperature in the insulated container remaining below 0°C during transit. They were then stored at −6°C in a freezer cabinet until the test specimens were prepared. Unfrozen blocks of iron ore were shipped in the normal manner.

Specimen Preparation and Test Procedures

Procedures similar to those described by King (1977) were employed in the preparation of the

TABLE 1. Physical properties of iron-ore test specimens

Specimen No.	Density, kg/m³ Saturated	Dry	Grain	Porosity	Water content,* kg/kg dry mass	Water saturation*
1	3370	3210	4570	0.30	0.05	0.53
2	3440	3230	4570	0.29	0.07	0.72
3	3350	3180	4570	0.30	0.05	0.55
4	3240	2920	4650	0.37	0.11	0.86
5	4250	4160	4540	0.08	0.02	0.92
6	4040	3900	4510	0.14	0.04	0.92
7	3760	3480	4860	0.29	0.08	0.92
8	3590	3270	4850	0.33	0.10	0.92
9	3630	3290	4930	0.33	0.10	0.92
10	3540	3190	4910	0.35	0.11	0.92
11	3550	3220	4810	0.33	0.10	0.92
12	3650	3330	4910	0.32	0.10	0.92
13	3520	3190	4780	0.33	0.10	0.92

Note: Specimen Nos. 1-4; naturally-occurring permafrost.
Specimen Nos. 5-13; unfrozen iron ore.
*Measured upon thawing.

permafrost test specimens. The cylindrical test specimens were 50 mm in diameter and approximately 80 mm in length. Immediately after preparation, the specimens were wrapped tightly and sealed in plastic film and then placed in a freezer cabinet maintained at −6°C. Specimens from unfrozen blocks of iron ore were prepared in the normal manner, as described by King and Pandit (1979). Again, the test specimens were 50 mm in diameter and approximately 80 mm in length. Specimens from the unfrozen blocks were fully saturated with distilled water under a vacuum. They were then wrapped tightly and sealed in plastic film and placed in a freezer cabinet maintained at −6°C until required for testing, together with the permafrost specimens. Four specimens (Nos. 1 to 4) of natural permafrost and nine (Nos. 5 to 13) of unfrozen ore were prepared. The physical properties of the test specimens are listed in Table 1.

Ultrasonic compressional and shear-wave velocities were measured on all four specimens of naturally-occurring permafrost at subzero temperatures, and for two of them (Nos. 3 and 4) at temperatures above 0°C. The specimens were subjected to a confining stress of 340 kPa throughout the tests. Three (Nos. 1, 2, and 3) of the four specimens were tested to failure under triaxial test conditions at a confining stress of 340 kPa, two (Nos. 1 and 2) at temperatures below 0°C, and No. 3 at a temperature of +2.8°C. Compressional and shear-wave velocities were measured during these tests, which were performed at an axial strain rate of approximately 10^{-3}/min.

Ultrasonic compressional and shear-wave velocities were measured on six (Nos. 5 to 10) of the nine water-saturated specimens of originally unfrozen iron ore at temperatures in the range −12 to +4°C. Ultrasonic velocities on the remaining three specimens (Nos. 11 to 13) were measured at subzero temperatures only. The first six specimens were tested to failure under uniaxial stress conditions at room temperature. Compressional and shear-wave velocities were measured during these tests, which were performed at an axial strain rate of approximately 10^{-2}/min. The remaining three specimens (Nos. 11 to 13) were tested to failure under triaxial stress conditions at a confining stress of 340 kPa at temperatures in the range −3.7 to −0.9°C. Compressional and shear-wave velocities were measured during these tests, which were performed at an axial strain rate of approximately 10^{-3}/min.

Results and Discussion

Compressional and shear-wave velocities are plotted for the four naturally-occurring permafrost specimens as a function of temperature increasing from −10 to +3°C (Figures 1 and 2) for a confining stress of 340 kPa and a major principal (axial) stress of 1.38 MPa. Results of the tests to failure on three of these specimens are shown in Figure 3, where the compressional and shear-wave velocities are plotted as a function of major principal stress to failure.

Compressional and shear-wave velocities in specimens of the originally unfrozen iron ore are plotted as a function of temperature increasing from −12 to +4°C (Figures 4 and 5) for a confining stress of 340 kPa and a major principal stress of 1.38 MPa. Compressional and shear-wave velocities are plotted in Figure 6 as a function of axial stress to failure for the six specimens tested to failure at room temperature, and in Figure 7 as a function of major principal stress to failure for the three specimens subjected to a confining stress of 340 kPa at subzero temperatures.

Compressive strengths at a confining stress of 340 kPa for the naturally-occurring permafrost and the three specimens (Nos. 11 to 13) of originally unfrozen iron ore are shown in Figure 8 plotted as a function of temperature. Compressive strengths for all specimens tested to failure are plotted in Figure 9 as a function of dynamic elastic modulus calculated from the saturated density and ultrasonic velocities.

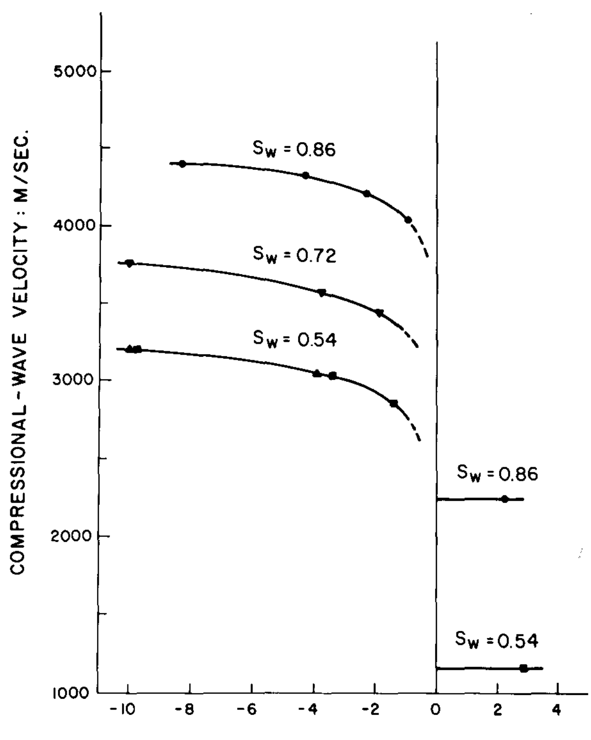

FIGURE 1. Compressional-wave velocities for four naturally-occurring iron-ore permafrost samples as a function of temperature: axial stress 1.38 MPa; confining stress 340 kPa.

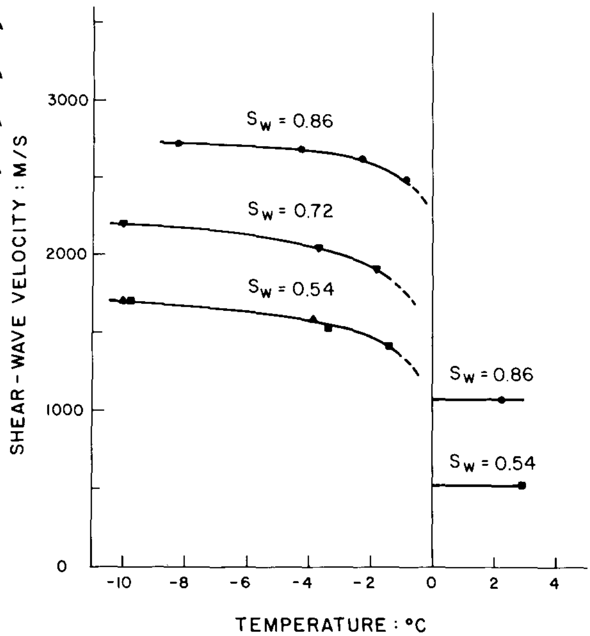

FIGURE 2. Shear-wave velocities for four naturally-occurring iron-ore permafrost samples as a function of temperature axial stress 1.38 MPa; confining stress 340 kPa.

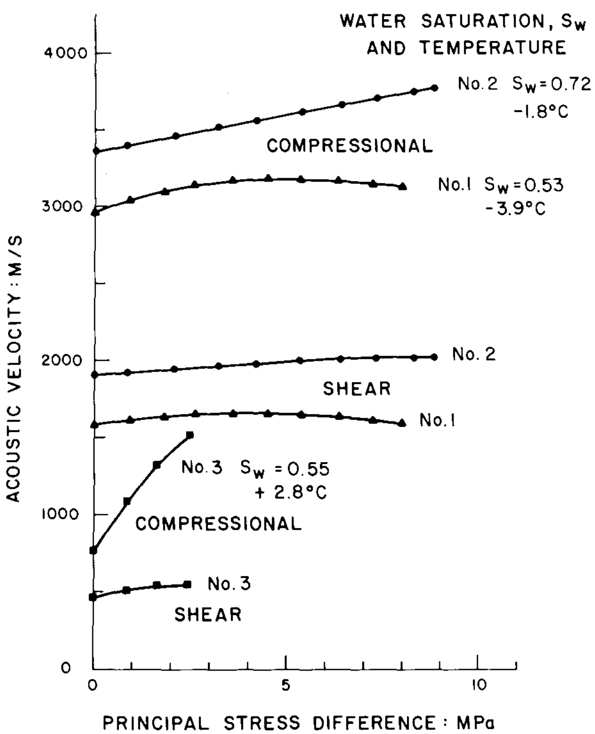

FIGURE 3. Compressional and shear-wave velocities for three iron-ore permafrost samples as a function of major principal stress to failure: confining stress 340 kPa.

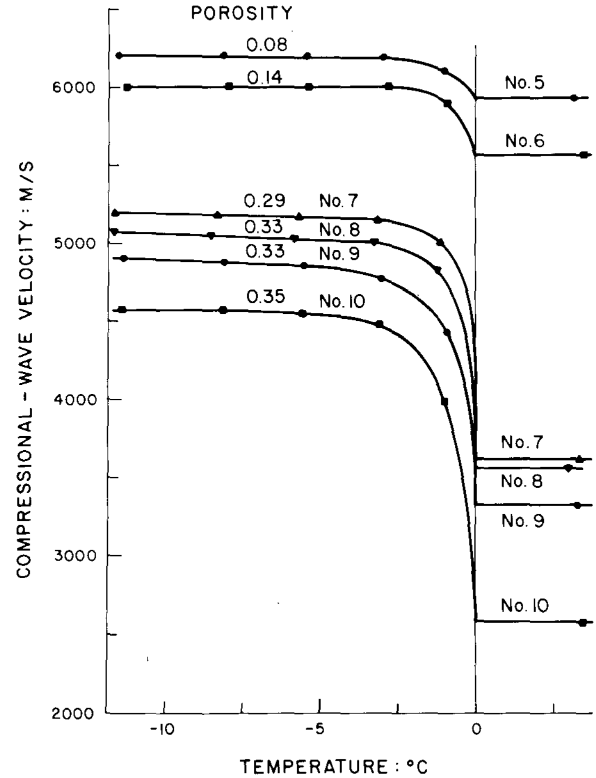

FIGURE 4. Compressional-wave velocities for originally unfrozen iron ore as a function of temperature: axial stress 1.38 MPa; confining stress 340 kPa.

Compressive strengths for specimens of approximately the same porosity are plotted in Figure 10 as a function of the compressional-wave velocity squared.

A study of the physical properties of specimens 1 to 4 provides an explanation for the differences in compressional and shear-wave velocities and compressive strengths for the naturally-occurring permafrost. In particular, it will be seen that the water saturations (fraction of pore space occupied by water) for these specimens ranges from 0.53 for specimen 1 to 0.86 for specimen 4. A frozen specimen with the pore spaces filled with ice will have a water saturation of approximately 0.92 upon thawing, due to the difference in density between ice and water. Figures 1 and 2 indicate the dependence of compressional and shear-wave velocities for permafrost on water saturation, as well as on temperature. Figure 3 indicates the marked dependence of compressive strength upon water saturation: the saturation of 0.72 for specimen 2 explains why it had a higher strength than specimen 1, with a saturation of 0.53, although the temperature at which specimen 2 was tested (– 1.8°C) was higher than that

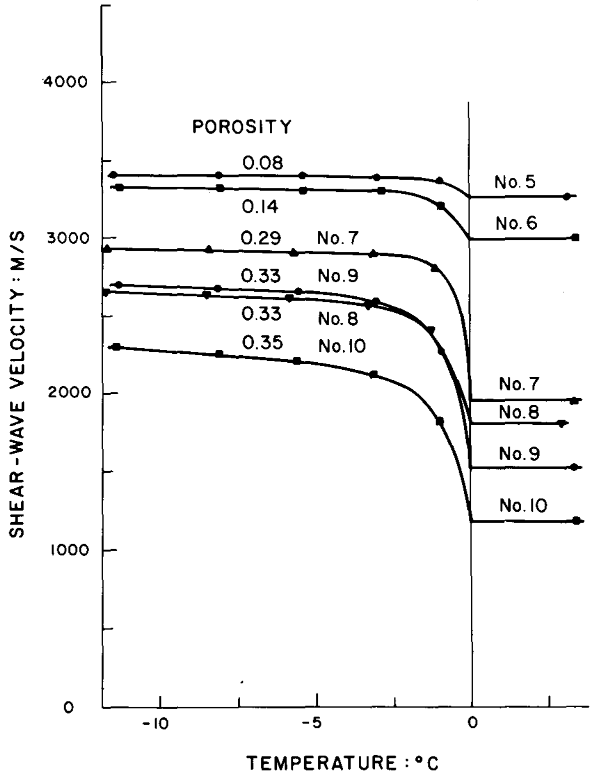

FIGURE 5. Shear-wave velocities for originally unfrozen iron ore as a function of temperature: axial stress 1.38 MPa; confining stress 340 kPa.

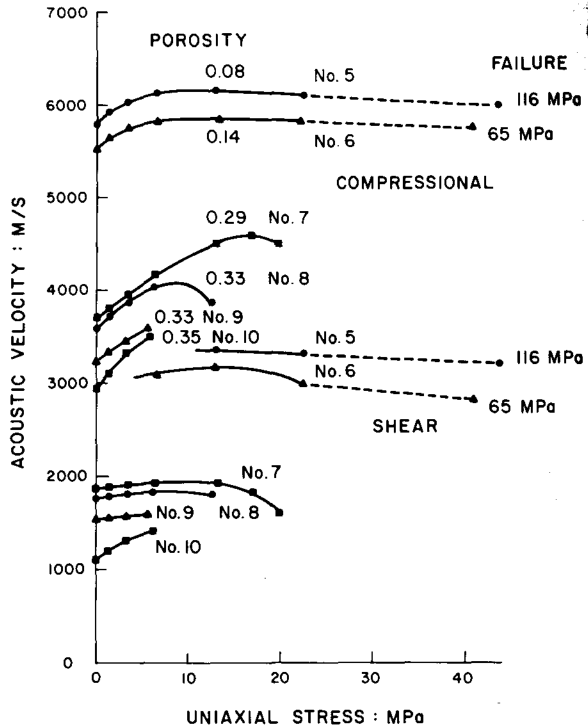

FIGURE 6. Compressional and shear-wave velocities for originally unfrozen iron ore as a function of uniaxial stress to failure at room temperature.

(−3.9°C) for specimen 1. This point is further illustrated (*see* Figure 8), where the strengths of the fully-saturated specimens of originally unfrozen ore are also shown.

Figures 4 and 5 show the influence of changes in porosity on the compressional and shear-wave velocities in iron ore fully water-saturated. It is seen that an increase in porosity or a reduction in water saturation results in a decrease in velocities, where the decrease is more marked in the thawed than in the frozen state. This serves to confirm Garg's (1973) observation that upon freezing, the massive iron ore becomes more homogeneous in its elastic properties, even though the water saturation and porosity may vary throughout the rock mass. In comparing Figure 4 with Figure 1, the compressional-wave velocities measured on two specimens, one from iron ore originally unfrozen (No. 10) and one from naturally occurring permafrost (No. 4) and having similar physical properties, are close in magnitude at temperatures over the whole range tested.

Figure 6 demonstrates the effect of porosity of iron ore on the compressional and shear-wave velocities and uniaxial compressive strengths of water-saturated iron ore. Figure 7 demonstrates the effect of changes of temperature on the compressional and shear-wave velocities and compressive strength of frozen, fully-saturated porous iron ore subjected to a confining stress of 340 kPa. The initial increases in compressional and shear-wave velocities observed with increasing principal stress, followed by decreases in velocities at higher stress levels, are similar in behaviour to those shown for the cemented unfrozen ore (*see* Figure 6). It is unlikely that the ice in the pore spaces was subjected to pressure melting at the comparatively slow rate of application of principal stress difference employed in these experiments. The effect of changes in water saturation on the compressive strength of naturally-occurring permafrost and originally unfrozen iron ore of approximately the same porosity at different temperatures is shown in Figure 8. A reduction in temperature or an increase in water saturation results in an increase in strength, although it is clear that more experimental data is required for partially-saturated iron ore.

The compressive strengths of all specimens tested are shown as a function of dynamic elastic modulus, calculated from the saturated density and compres-

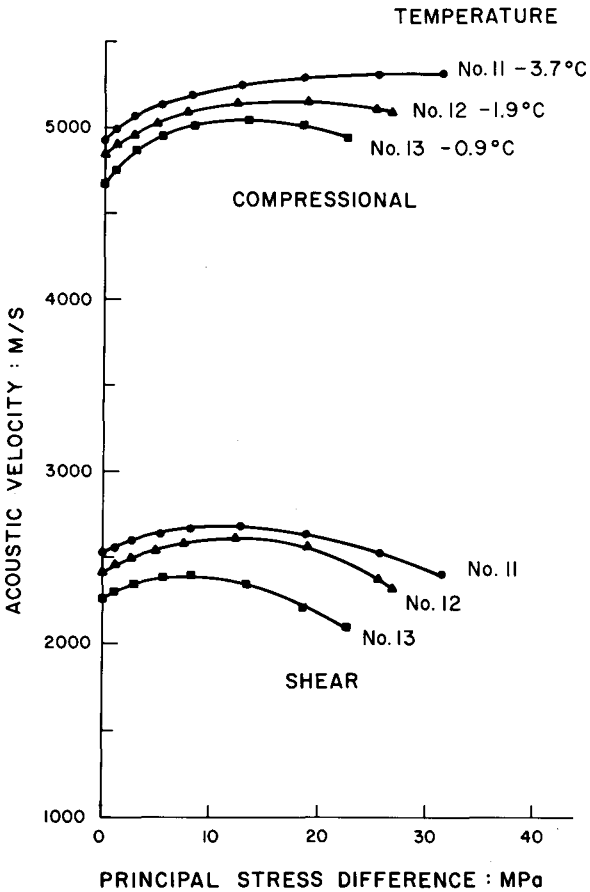

FIGURE 7. Compressional and shear-wave velocities for originally unfrozen iron ore as a function of major principal stress to failure at subzero temperatures: confining stress 340 kPa.

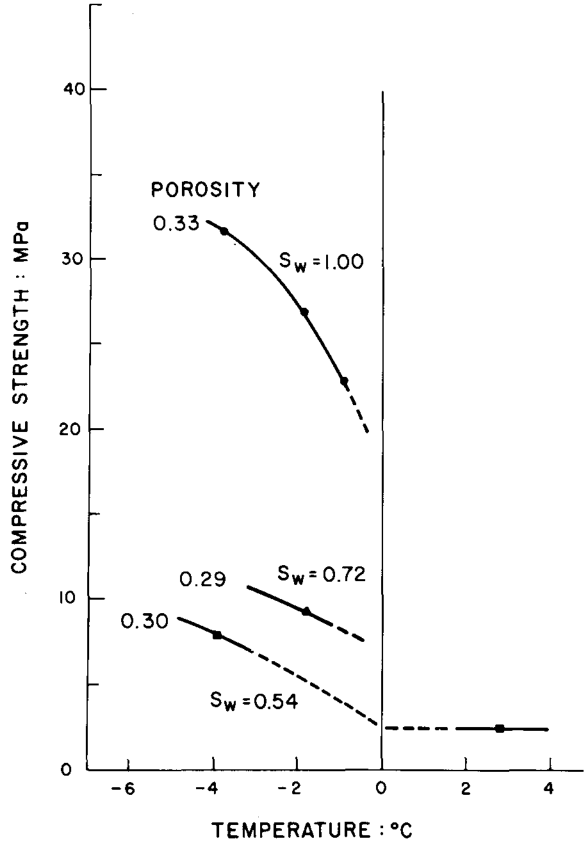

FIGURE 8. Compressive strengths of naturally occurring permafrost and originally unfrozen iron ore as a function of temperature for different water saturations (S_w): confining stress 340 kPa.

sional and shear-wave velocities (Garg 1973), in Figure 9. Note that whereas six specimens (Nos. 5 to 10) were tested at room temperature under uniaxial compression, the remainder (Nos. 1 to 3 and 11 to 13) were tested under triaxial test conditions at a confining stress of 340 kPa. Nevertheless, calculations using a modified Griffith failure criterion for the iron ore indicate that the increase in strength resulting from the application of 340 kPa confining stress would be less than 10 per cent. At low values of compressive strength and dynamic elastic modulus there appears to be a fair correlation between these parameters.

Compressive strengths of fully and partially water-saturated iron ore of approximately the same porosity, frozen and unfrozen, are shown (*see* Figure 10) as a function of compressional-wave velocity squared. There is a good linear correlation between these parameters. Data from Zykov *et al.* (1978) for frozen water-saturated sand of 0.40 porosity fall close to, but slightly below, the correlation shown for iron ore. However, it is not clear in what way these authors measured the compressive strength of the frozen sand they tested.

Conclusions

1. Compressional and shear-wave velocities measured at subzero temperatures on permafrost and originally unfrozen iron ore are approximately the same, provided the ice content and porosity are equivalent.

2. Compressional and shear-wave velocities and the compressive strength of frozen and thawed iron ore are strongly influenced by the magnitude of porosity and initial ice content. The velocities and strength increase as the porosity decreases or as the initial ice content increases.

3. With regard to its elastic properties, massive iron ore is more homogeneous in its frozen state than when thawed even though the porosity and ice content vary throughout the rock mass.

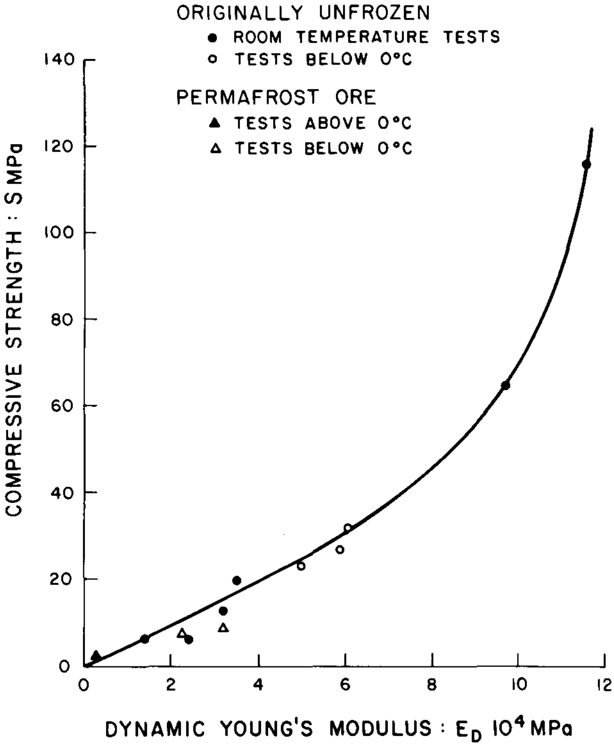

FIGURE 9. Compressive strengths (S) of all samples tested as a function of dynamic elastic modulus (E_D).

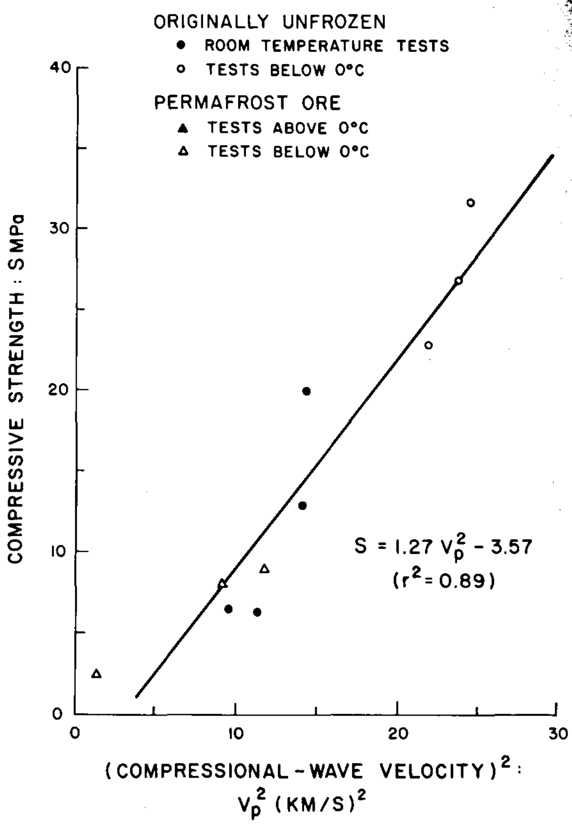

FIGURE 10. Compressive strengths (S) of samples of approximately the same porosity as a function of compressional-wave velocity squared (V_p^2).

4. A correlation exists between the compressive strength of frozen and unfrozen iron ore and the dynamic elastic modulus calculated from the ultrasonic velocities and density.

5. A good correlation exists between the compressive strength of frozen and unfrozen porous iron ore and the square of the compressional-wave velocity. Seismic surveys may therefore be expected to provide a good estimate of the strength of iron ore.

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