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ICE ENGINEERING: ELASTIC PROPERTY STUDIES ON COMPRESSIVE AND
FLEXURAL SEA ICE SPECIMENS

By

K. D. Vaudrey

December 1975

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INTRODUCTION

The scientific, commercial, and military communities are showing increased interest in the polar regions. In particular, Naval operations in both the Arctic and Antarctic depend on sea-ice airfields to provide heavy cargo and aircraft support. Therefore, a better understanding of the behavior of sea-ice sheets under aircraft loading is required to ensure continued safe operations. To this end, the Civil Engineering Laboratory (CEL) has undertaken a comprehensive research program to perform experiments both in the laboratory and in the field, leading to the development of rational analytical models to predict sea-ice behavior [1-3]. Both elastic and viscoelastic finite element computer codes have been written to analyze sea-ice sheet behavior.

During FY-74 and FY-75, as a continuation of this study on the strength and behavior of sea ice, both laboratory and field experiments were performed on compressive and flexural sea-ice specimens. These tests were designed to achieve the primary objective of establishing reliable material property values for the elastic modulus and allowable failure strength. These material properties are necessary input for the analytical models to predict future sea-ice behavior under complex loading configurations.

COMPRESSIVE STRENGTH

Laboratory and Field Test Results

Both extensive laboratory and Antarctic field studies were performed on right-circular cylinders of sea ice loaded elastically in compression to failure. Each specimen had a length-to-diameter ratio of 2:1. The laboratory test series included four test temperatures (-4° , -10° , -20° and -27° C), two crystal orientations (horizontal and vertical), and one salinity level (7 to 9 ppt). The sample size ranged from 46 to 81 for each of these eight combinations of sensitive parameters. Load-head speed was kept constant at 0.5 in./min, producing a strain rate on the order of 10^{-3} in./in./sec. Both the load and longitudinal deflection were monitored during each test.

The field test series included just two ice temperatures (-4° and -10° C) and only the vertical crystal orientation. The salinity range (4 to 6 ppt) was considerably lower than normal young sea ice, since the test specimens were extracted from year-old sea ice.

The compressive strength results are plotted in Figure 1 as a function of the ice temperature. The average of each sample group is shown with a 95% confidence limit. These statistical limits indicate that if another sample group were to be taken there would be a 95% chance the mean of that sampling would lie within the confidence interval. Both the vertical and horizontal results are connected by a dotted line to demonstrate the general trend of increasing strength as the temperature decreases. The field data points show higher compressive strength than the laboratory tests at the same temperature. The lower salinity of the 1-year-old ice in the field is a major contributor to the additional strength.

Previous laboratory effort on the tensile strength of 7-to-9-ppt sea ice is shown in Figure 2. Again, test results are shown for the same four ice temperatures and crystal orientations. The average of each laboratory sample group is plotted between the limits of the 95% confidence level.

While every attempt was made to eliminate salinity as a variable, the average salinity varied 1 to 2 ppt within the 7-to-9-ppt range. Therefore, a parameter called the brine volume, a combination of temperature and salinity, is often used to compare relative strengths of sea ice. In Figure 3 both horizontal and vertical compressive strength are plotted as a function of the square root of brine volume, using a regression technique called the least-squares method. By this method different data groups, shown as individual points in Figure 3, are averaged, weighted by the amount they differ from the mean, and approximated by straight lines governed by the following equations:

$$\text{Horizontal compressive strength} = 825 - 60.1 \sqrt{\text{brine volume}} \quad (1)$$

$$\text{Vertical compressive strength} = 1,628 - 79.2 \sqrt{\text{brine volume}} \quad (2)$$

The y-intercept of the above equations simply indicates the compressive strength of fresh ice, since the value for the brine volume would be zero. The negative slope shows that the brine volume increases with higher salinities and temperatures; hence, the strength of ice deteriorates.

It is interesting to compare least-squares analyses of previous tensile tests and the recently completed compression experiments. The straight line approximations for the laboratory tensile strength specimens are given in Equations 3 and 4 and are plotted in Figure 4. Both Equations 3 and 4 include tensile strength data from 1-to-2-ppt salinity ice specimens as well as from the 7-to-9-ppt tests.

$$\text{Horizontal tensile strength} = 118 - 10.0 \sqrt{\text{brine volume}} \quad (3)$$

$$\text{Vertical tensile strength} = 224 - 12.7 \sqrt{\text{brine volume}} \quad (4)$$

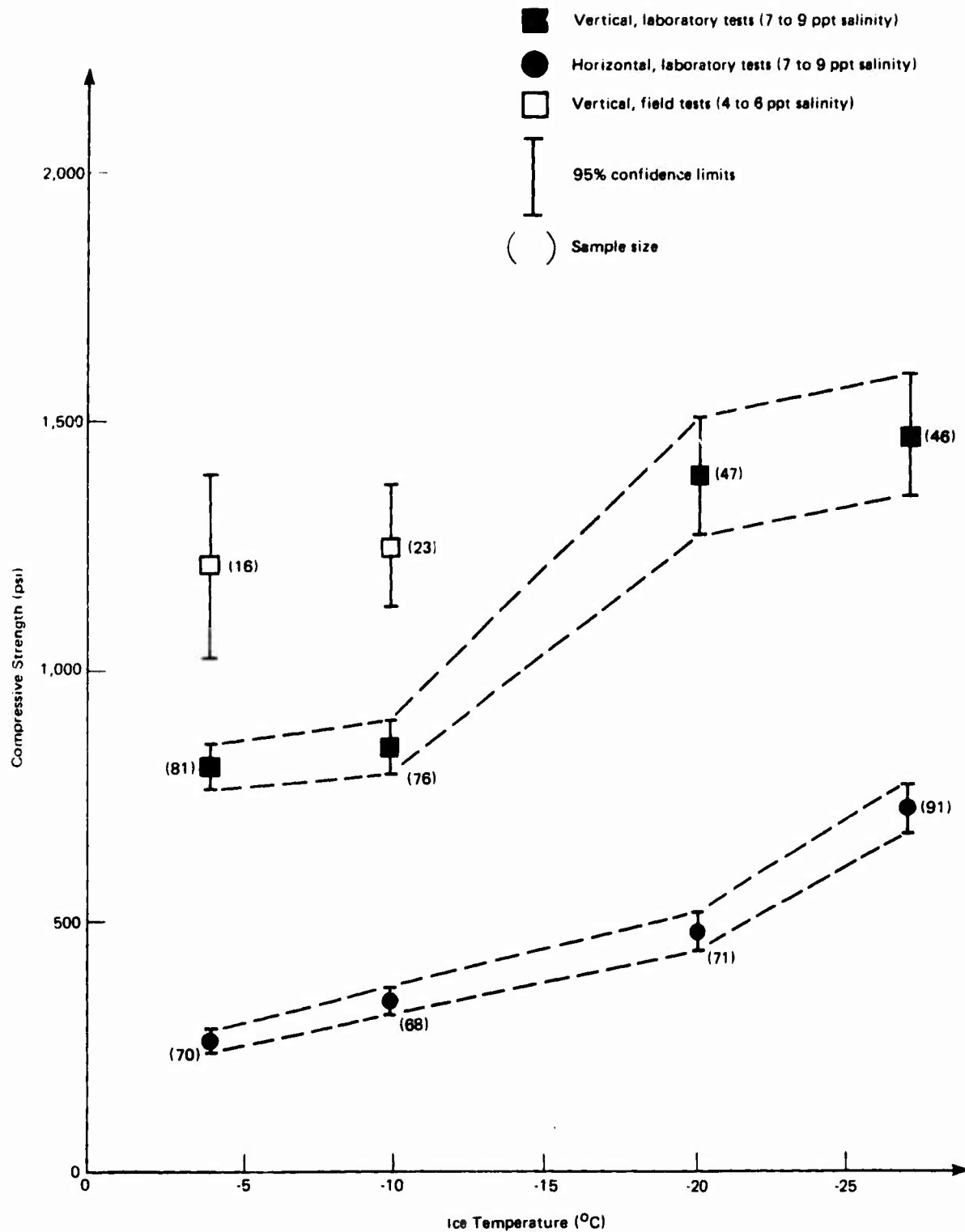


Figure 1. Compressive strength versus ice temperature.

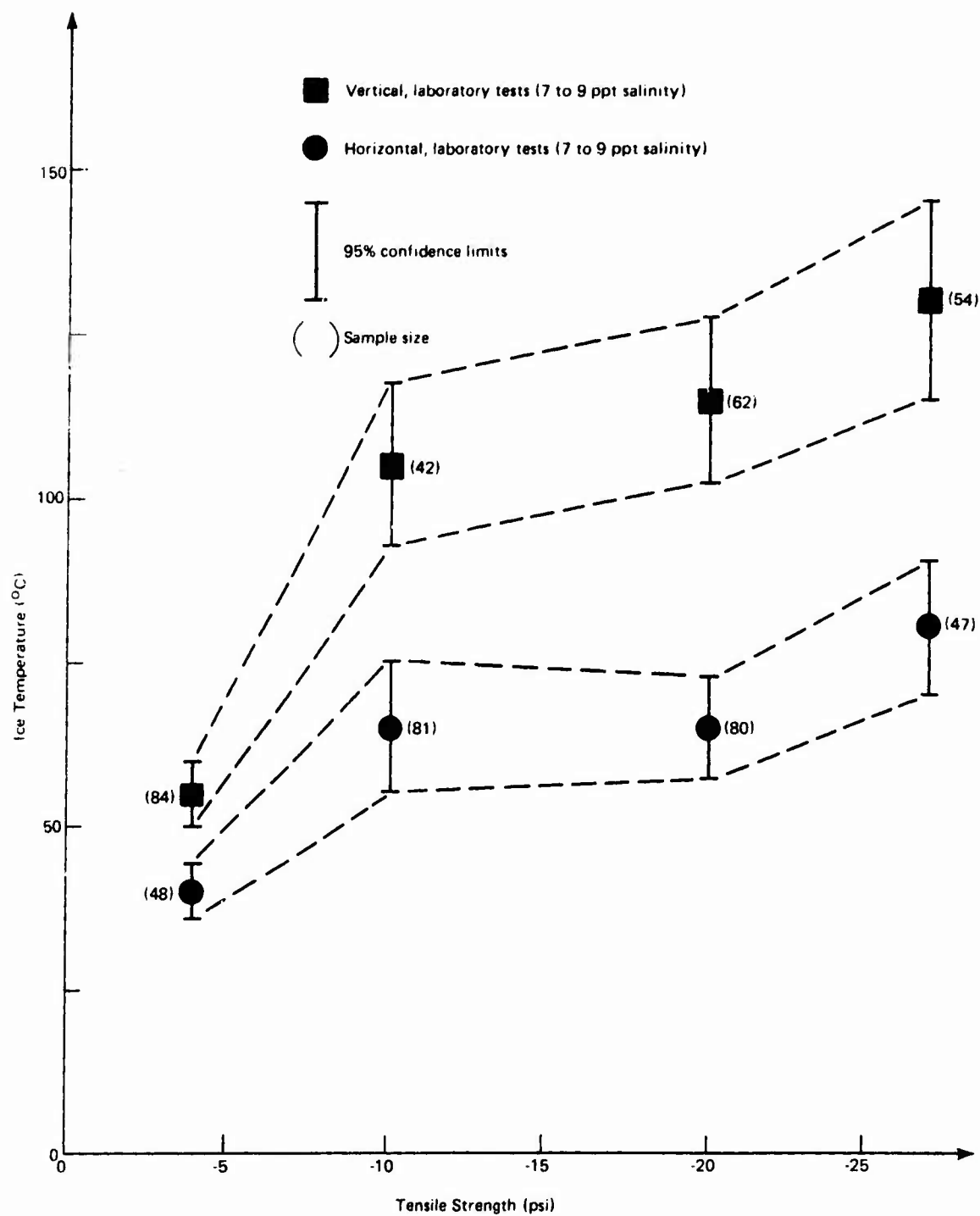


Figure 2. Tensile strength versus ice temperature.

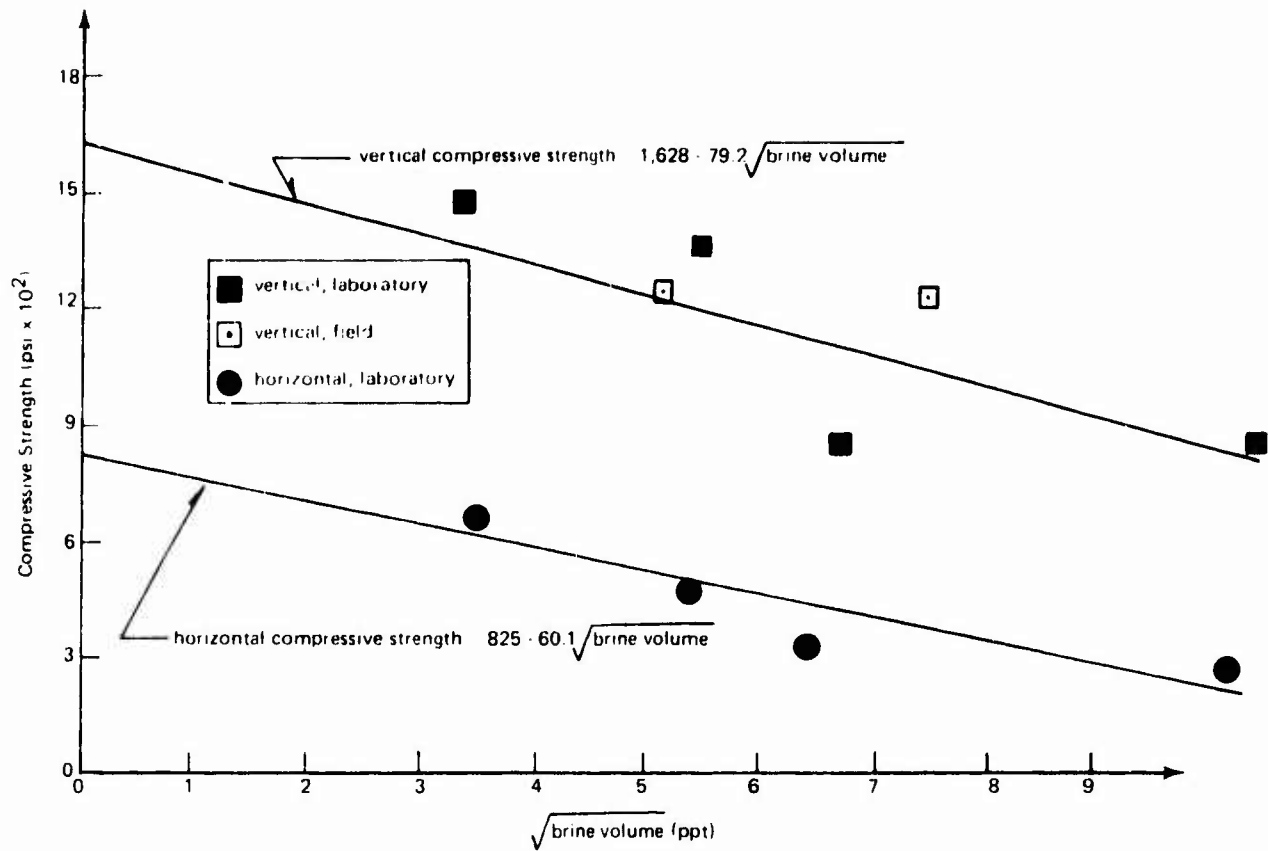


Figure 3. Compressive strength versus brine volume.

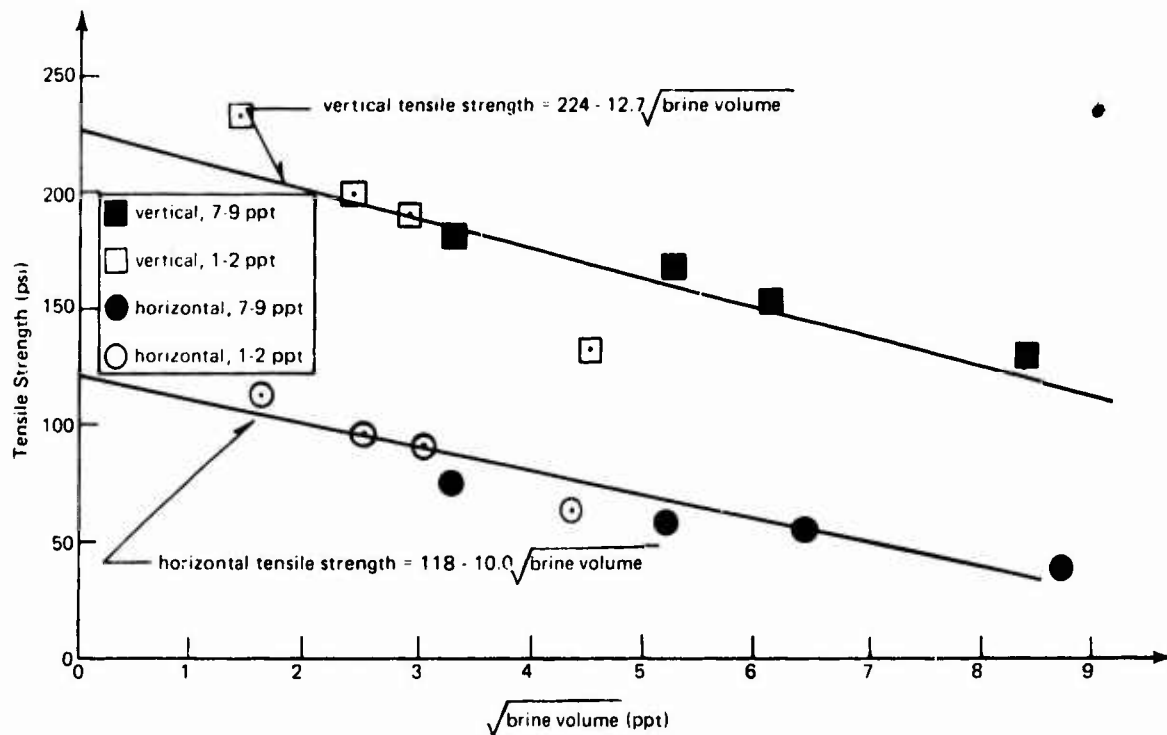


Figure 4. Tensile strength versus brine volume.

Two different, yet significant, comparisons can be made of the ratios showing the relationships (1) between tensile and compressive strengths for each crystal orientation and (2) between horizontal and vertical crystal orientation for each loading mode. First, both the horizontal and vertical compressive-to-tensile strength ratios are approximately 7:1, using the freshwater ice values for comparison. Second, both the compressive and tensile vertical-to-horizontal strength ratios are approximately 2:1, again comparing zero brine volume values.

Compressive Failure Modes of Sea Ice

The modes of failure of compressive sea-ice specimens vary, depending on the ice temperature, crystal orientation, end restraints, and strain rate during testing. The strain rate was held constant at 10^{-3} in./in./sec for these particular tests. Of course, compression itself does not tend to form or propagate cracks and, thus, cause failure. But the same does not hold true for the secondary tensile and shear stresses generated during uniaxial compression [4]. In brittle materials, such as very cold sea ice, tested at relatively high strain rates shear fractures inclined to the compression axis are quite common (Figure 5). In cylindrical specimens, typical shear fractures can propagate part way along the boundary of a cone, and then the separated conical section can wedge the rest of the specimen apart, as shown in Figure 6.

Another typical failure mode of cylindrical specimens is fracturing along a plane parallel to the compression axis, termed axial cleavage and caused by secondary tensile stresses in the end thirds of the specimen. Theoretically, these tensile stresses can attain values up to one-half of the axial compressive stress, but they generally are suppressed by friction between the heads of the testing machine and the specimen. This end restraint causes an abnormal increase in the required compressive load in order to build up the tensile stresses sufficiently to cause failure. End confinement can be reduced by placing low friction material, such as Teflon, between the load-heads and specimens. Alternatively, platen-specimen matching can provide the condition of equal radial strain by forcing the quotient of Young's modulus of elasticity divided by Poisson's ratio to have the same value for both specimen and platen materials [5]. However, during the tests such attempts became impractical, and to compensate for end confinement, specimens with $L/D = 2$ were used to provide a mid-section that was reasonably free of frictional-restraint effects. In addition, brittle materials with large crystalline structure, such as sea ice, generally have low shear strengths, and the failure mode will most likely be one of shearing; thus, end restraint produces little effect on failure modes.

Almost all of the horizontal ice specimens tested in compression failed in shear, with higher temperature (-4° and -10°C) specimens failing less demonstrably than those at lower temperatures; that is, they developed a series of small, criss-crossing shear cracks but remained intact. The greater density of brine inclusions at these higher ice

temperatures may create more points of stress concentration which ultimately reduce the load-carrying capacity of the specimen without its destruction. At lower temperatures a more definitive shear plane develops, because the sea ice has become a more homogeneous crystalline material after increasing salt precipitation.

Occasionally vertical ice specimens demonstrated a cleavage failure. This is because the secondary tensile stresses developed perpendicular to the crystal growth tend to separate crystals at their boundaries or within crystals at platelet boundaries. This failure mode may govern, particularly under higher load rates (~ 300 to 400 psi/sec), since these tensile stresses develop spontaneously as axial compression is rapidly applied.

FLEXURAL STRENGTH

Previous laboratory and field experiments were performed to investigate the flexural strength and to determine the elastic modulus of sea-ice beams. A group of laboratory and small field beams, which were tested to fill out the data deficiency at -20°C , and supplemental field tests on large in-situ beams have completed the CEL effort on elastic flexural strength. The laboratory and small field beams all had nominal dimensions of $2 \times 2 \times 16$ inches. All specimens were horizontal beams and were tested so that the normal vertical ice crystal growth acted in the same plane as the load. All FY-74 large field specimens were tested in-situ on both cantilever and simply supported beams having nominal 40-inch-wide by 65-inch-deep cross sections and ranging from 35 to 55 feet in length. Previous large field tests were performed on specimens of varying dimensions: 40 inches wide by 72 to 96 inches deep and ranging from 50 to 100 feet long.

Both the new laboratory and field data were incorporated with previous flexural strength tests, which are plotted in Figure 7 as a function of temperature. The data span a temperature range from -2°C to -28°C . Each individual field data point is plotted at the average temperature for beams having a thermal gradient, while the average of each isothermal laboratory group is shown with a 95% confidence level. The laboratory data at -20°C fills a previous void in flexural strength analysis, and all of the results shown in Figure 7 represent a complete strength-temperature history for sea-ice beams.

Following the same analytical technique used to relate tensile and compressive strength to the combined effect of salinity and temperature, the flexural strength is shown in Figure 8 as a function of the square root of the brine volume present in the ice. The data are plotted using the individual field data points and the mean value for each laboratory sample group. A weighting factor is applied to give more significance to the field tests by assuming that 25 laboratory specimens equal one large-scale field test. The equation of the straight line based on least-squares analysis is:

$$\text{Flexural strength} = 139.12 - 8.82 \sqrt{\text{brine volume}} \quad (5)$$



Figure 5. Horizontal, compression specimen tested at -20°C , showing typical shear failure.



Figure 6. Horizontal, compression specimen tested at -27°C , showing typical shear failure.

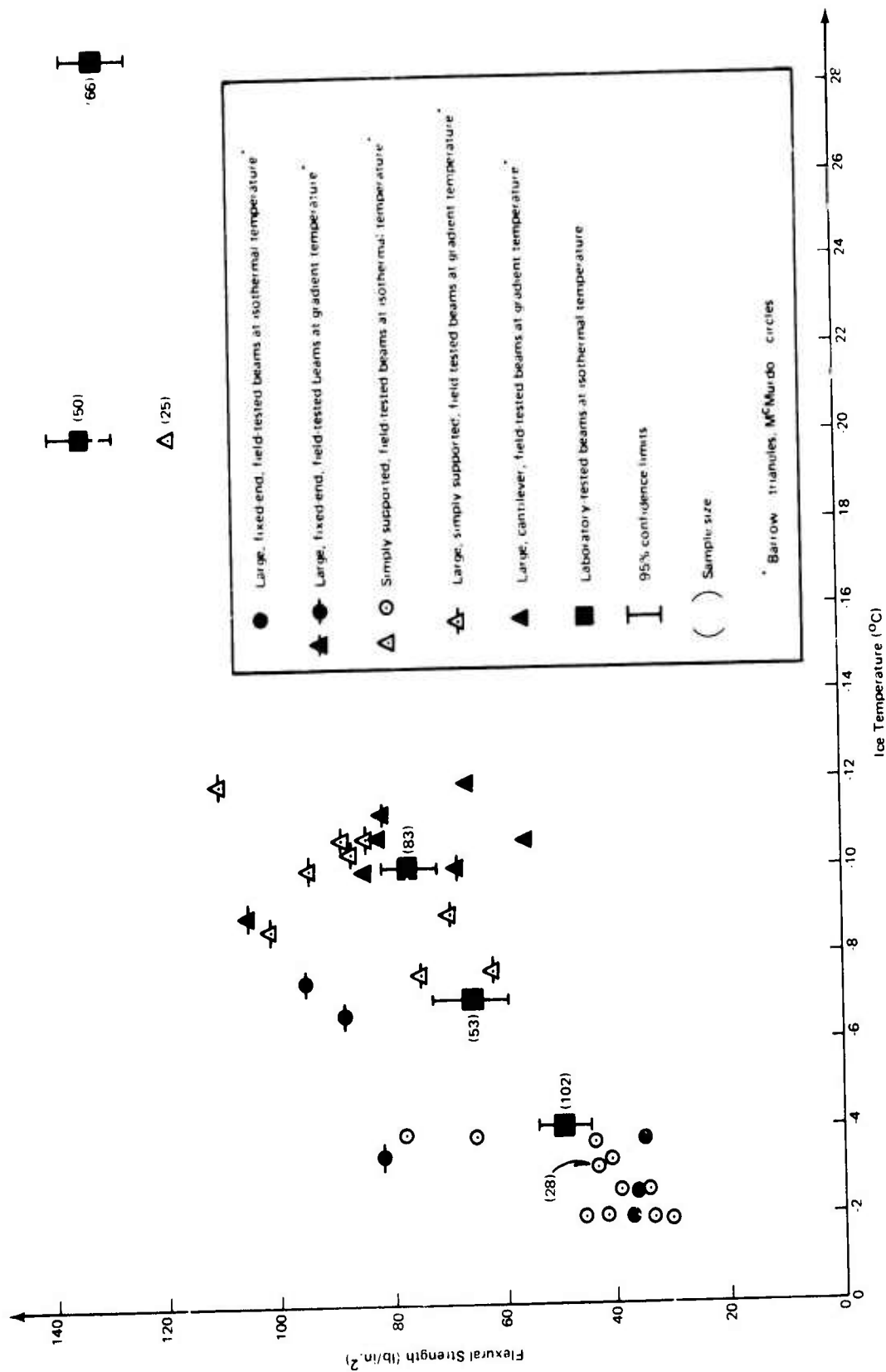


Figure 7. Flexural strength versus ice temperature.

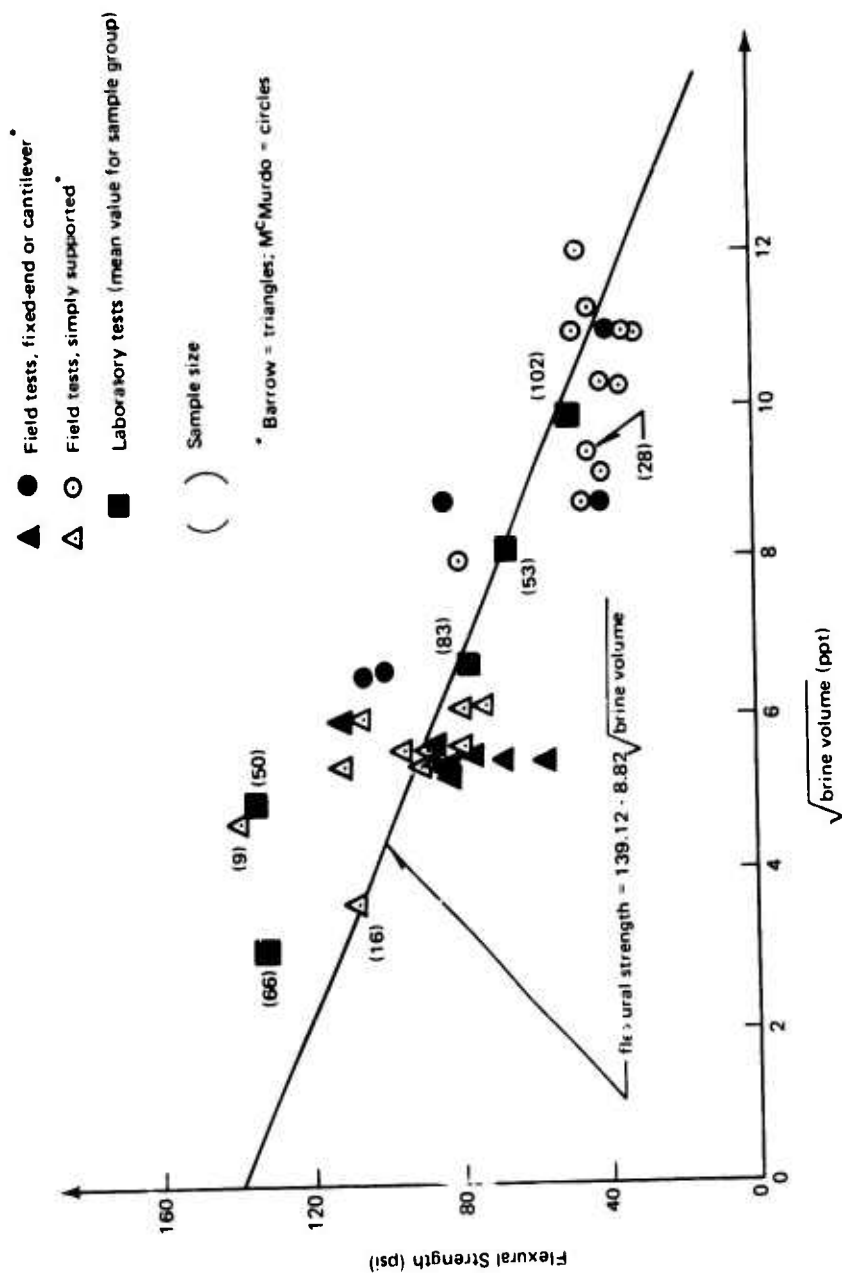


Figure 8. Flexural strength versus brine volume.

if one extends the line of Equation 5 until it intercepts the flexural strength axis, it is found that the flexural strength is about 140 psi for freshwater ice (zero brine content).

MODULUS OF ELASTICITY

In addition to determining the tensile and compressive strengths, the single most important material property of sea ice is the elastic or Young's modulus of elasticity. This material property is necessary as an input parameter to a finite element computer code, which provides a quick and accurate tool for solving generalized sea-ice problems.

The easiest method for finding the modulus of elasticity is to measure the strain corresponding to a given stress state in a right circular cylinder subjected to either pure compression or tension. Over 300 compression specimens, with a length to diameter ratio of 2:1, were tested in the laboratory at four different ice temperatures and for both vertical and horizontal crystal orientation. Deflection measurements were recorded by extensometers, having a gage length of 2.375 inches, bonded directly to each specimen by freshwater ice; the results of those tests are shown in Figure 9. The tests were performed on specimens cored both perpendicular to (horizontal) and parallel to (vertical) the direction of crystal growth. The elastic moduli values are considerably greater for "vertical" sea-ice specimens than for "horizontal" specimens.

Another method of determining the modulus of elasticity is to measure the strain at the location of the maximum fiber stress on sea-ice beams. The testing program on sea-ice beams was completed with the laboratory effort on small (2 x 2 x 16-in.) simply supported beams subjected to a two-point loading at -20°C. Again deflection is measured by extensometers bonded to the underside of each beam. In addition to the laboratory experiments, large-scale (40-inch wide by 65-inch deep by 50-foot long) cantilever and simply supported beams were tested near Barrow, Alaska, on the Chukchi Sea during FY-74. Deflections were recorded by a 6-inch stroke LVDT. Results from past flexural beam tests, as well as the recent laboratory and field efforts, are shown as a function of temperature in Figure 10.

Moduli values for the horizontal compressive tests are lower than those found from flexural beam tests. A combination of load-rate effects, end conditions, and the difference between compressive and flexural strength may have caused the discrepancy in the elastic moduli values. Both test series were run with a constant (0.5 in./min) load-head speed. This loading speed develops compressive stress at a slower rate, but ultimately to a higher level, possibly causing either a visco-elastic or nonlinear response of the specimen, or both. On the other hand, flexural specimens attain their maximum stress quickly and fail elastically in tension, before the compressive stress can build up to a level producing a nonlinear or rapid-creep response.

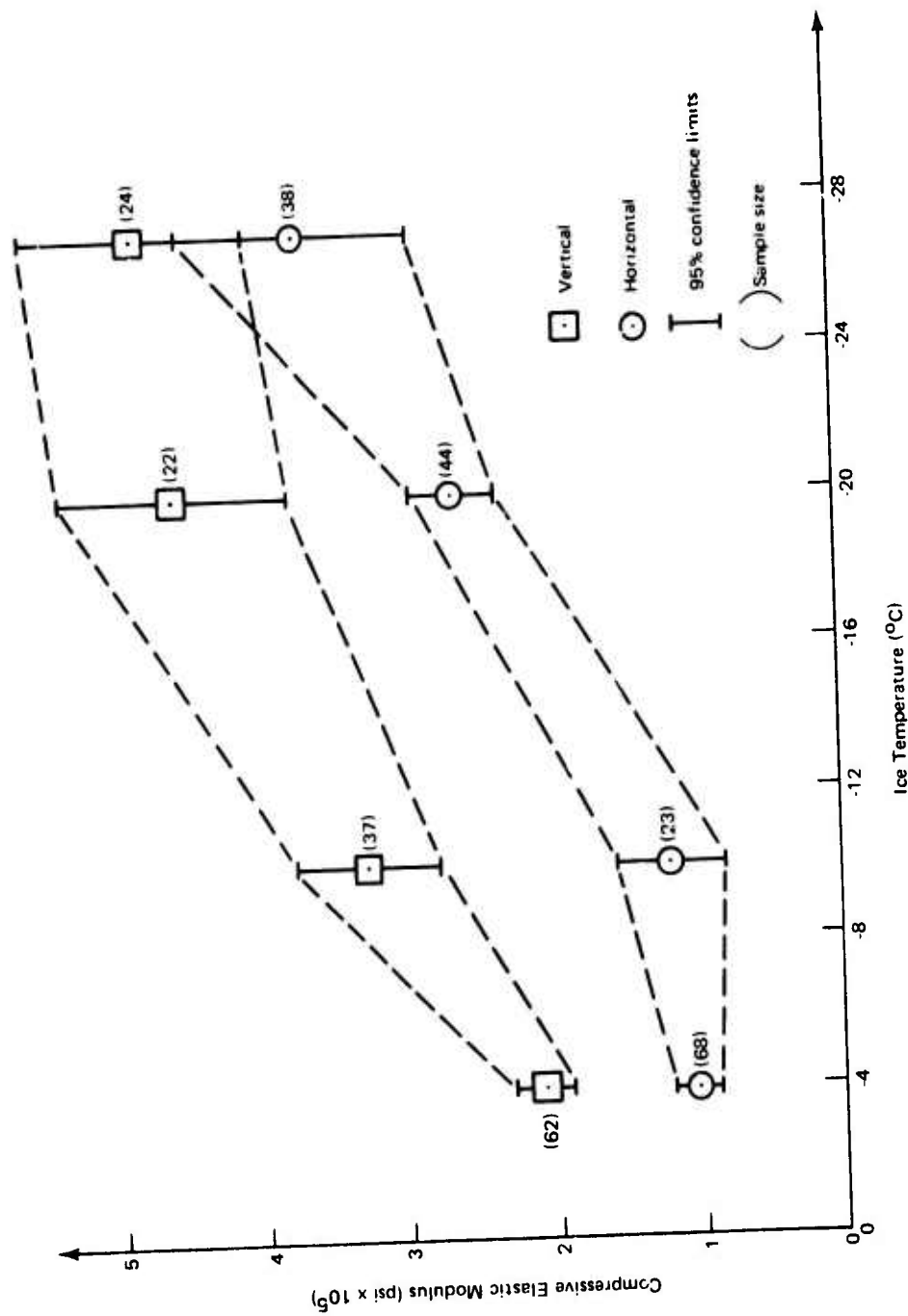


Figure 9. Compressive modulus of elasticity versus ice temperature.

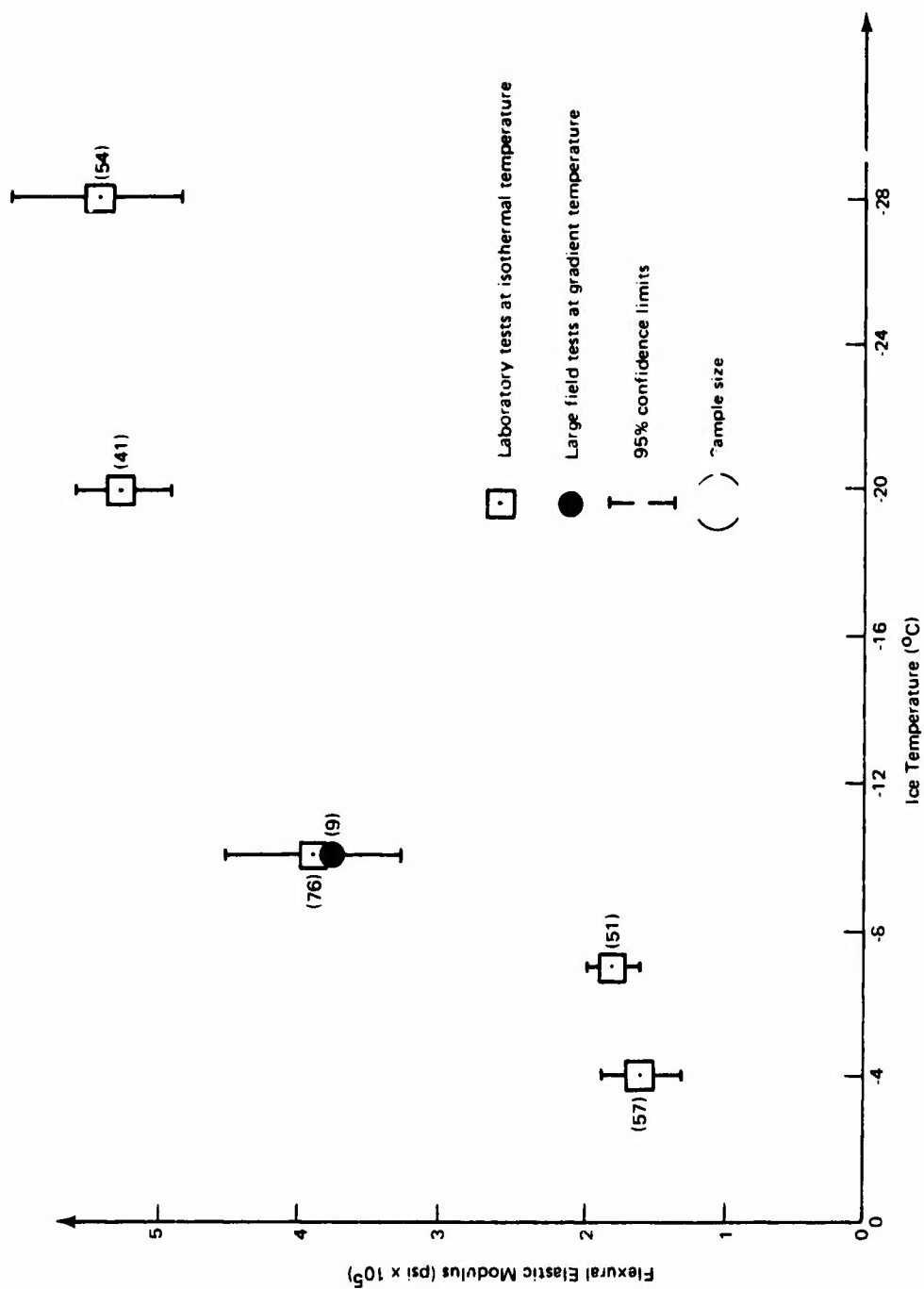


Figure 10. Flexural modulus of elasticity versus ice temperature.

CONCLUSIONS

The effort covered by this report culminates years of elastic sea-ice testing by CEL. When the tensile, compressive, and flexural tests are combined, the magnitude of the data is significant, approaching 1,500 individual specimens. Needless to say, there has been a greatly increased understanding in the elastic material properties and behavior of sea-ice sheets. In considering the thermal-dependent and orthotropic behavior, several important conclusions can be gleaned from comparison of various data analyses.

1. Both horizontal and vertical compressive-to-tensile strength ratios are approximately 7:1.
2. Both compressive and tensile vertical-to-horizontal strength ratios are approximately 2:1.
3. Shear fracture was the most frequently observed failure mechanism during tests on compressive sea-ice specimens.
4. A complete flexural strength-temperature history for sea-ice beams has been compiled covering the temperature range of -2° to -28°C .
5. The elastic modulus of sea ice is temperature-dependent and ranges from 1.5 to 6.0×10^5 psi.

RECOMMENDATIONS

1. Additional experimental effort on the viscoelastic properties of sea ice should be performed in order to predict the response of an ice sheet to parked aircraft and cargo storage.
2. Further analysis of fracture mechanisms of sea ice should be performed to develop adequate failure criteria for ice sheets.
3. Further compression tests should be performed on brackish-water ice (1-to-2-ppt salinity) to complete the compressive strength laboratory effort. These tests would provide the opportunity to evaluate and verify testing conditions (e.g., load-rate and end-constraint effects).

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