A new type of model ice has been developed for use in refrigerated towing basins. The ice is grown from an aqueous solution containing three different chemical dopants – ethylene glycol (EG), aliphatic detergent (AD) and sugar (S). In this paper, the concepts and development of this model ice are discussed. Analysis of the structure of the ice indicates that it is single layered, fine-grained and strictly columnar. A number of the mechanical properties of EG/AD/S model ice have been measured including the flexural strength, uni-axial and confined compressive strength, strain modulus and critical stress intensity factor. The results of these tests are compared to appropriately scaled sea ice values and the corresponding properties for carbamide (urea) model ice. This comparison shows that this new ice is far superior to urea model ice in all respects.

1.0 INTRODUCTION

Physical modelling of an ice-structure interaction has become an important technique in determining the ice loads and optimizing the design of ice breaking vessels, Arctic drilling platforms, etc. Currently there are a number of ice modelling basins in several countries including Canada, U.S.A., Germany, Finland and Japan. With this technique, the important forces in the interaction process are maintained in the same ratio as in the prototype but at a reduced scale. For accurate results, the appropriate scaling laws must be used. This places restrictions on the size and mass of the model structure and on the model ice used in the tests. For most investigations, Froude and Cauchy scaling laws are used so that the prototype structure is reduced in its linear dimensions by a constant value \( \lambda \) which is greater than one. This then defines the scale factor for the test. Knowing this, the properties of the model ice must be adjusted such that its strength (compressive, flexural, shear and tensile), stiffness and thickness must be reduced from the full scale or prototype value by \( \lambda \), but its density and frictional characteristics must be the same as the full scale values. For accurate model test results, it is important that the model ice be an accurate representation of the prototype ice (either freshwater ice or sea ice; see Timco (1984a) for a recent review).

In the first modelling tests with ice in Leningrad in 1957 (Shvayshteyn, 1957), the model ice was produced by freezing an aqueous solution containing a relatively high (\( \approx 3\% \)) concentration of sodium chloride salt. The salt was trapped within the ice and by internal melting, reduced the strength of the ice. This type of ice however, was not satisfactory because its stiffness (or strain modulus) was far too low and the ice exhibited unrealistic plastic deformation. Schwarz (1975) developed a tempering technique whereby sheets of ice were frozen from solutions containing a low concentration of sodium chloride (0.6%) and by warming up the ice after the freeze, an ice sheet with a more accurately scaled stiffness would result. This technique, however, was usable only for scale factors up to \( \lambda = 15 \) and so it was somewhat limited. Timco (1979) reported on
a series of tests in which he grew model ice sheets from a number of solutions which contained chemicals or dopants from various families of chemicals including the chlorides, sulphates, alcohols, amides, salts of fatty acids and sugars. He found that ice doped with a chemical from the amide family — carbamide (which is more commonly known as urea) — produced model ice sheets with better mechanical properties than sodium chloride doped ice. This finding was received with enthusiasm by many of the ice modelling basins and ice doped with carbamide (or urea) became the standard model ice in most refrigerated tanks in the world. The properties of this ice have been measured and well documented in the literature (Timco, 1980, 1981a, 1983a, 1983b, 1984a, 1985; Sandell, 1981; Hirayama, 1983a, 1983b; Gow, 1984). This ice is columnar in structure but consists of a thin mechanically strong upper layer, a thin transition layer and a weak lower layer. This layered system affects some of the ice properties. In general, for this ice, the flexural strength, shear strength, compressive strength, density, friction and stiffness are scaled well but the fracture toughness and full anisotropy of the ice are incorrectly scaled. Thus, although this ice does not accurately represent sea ice in all respects, it is generally regarded as the current state-of-the-art in refrigerated model ice. Most recently, a new type of fine-grained model ice was developed by Enkvist and Makinen (1984) based on a technique involving continual spraying of sodium chloride solution throughout the growth process. This produces a fine-grained granular-structured model ice which has several promising features. Unfortunately, however, the granular structure limits the use of the ice since it does not accurately represent the structure of sea ice which is mostly columnar. This does not allow the ice to be scaled correctly in either uni-axial compressive strength or confined compressive strength. This may lead to a premature ice failure and a corresponding under-prediction of the loads on the full-scale structure (Timco, 1984b; Wang, 1984).

Through the evolution of each of these types of model ice, considerable insight has been gained into the mechanisms of ice growth, the resulting properties, and the advantages and shortcomings of each type of ice. In total, it is clear that there is no perfect model ice — nor will there ever be, considering the complexity of the material which is being scaled. However, from work with the present day model ice it is now possible to indicate the features which an ideal model ice should have. Sea ice is mostly columnar (Weeks and Ackley, 1982) and since the structure controls the mechanical properties, it is clear that the model ice must be columnar-structured. Moreover, in order for the model ice to behave as an anisotropic but homogeneous material, it must be single-layered with a uniform distribution of low molecular weight dopant molecules throughout the ice. For proper structural simulation at a reduced scale, the ice must also be extremely fine-grained. With this goal in mind, a new type of model ice has been developed in the ice tank in the Hydraulics Laboratory of the National Research Council of Canada in Ottawa. It is a refrigerated model ice which is grown from a solution containing three different chemical dopants, each of which is designed to alter the structure and properties of the ice in a specific way.

In this paper, the development of this ice is described. By reviewing the mechanisms of growth from impure melts, the means of chemically altering the structure of the ice are elucidated, and the types and properties of the chemicals necessary to produce the appropriately-structured model ice are identified (Section 2.0). Based on this, suitable candidate dopants are chosen (Section 3.0). Using these, a new type of model ice has been developed (Section 4.0) and its mechanical properties have been measured. These include the flexural strength, uni-axial and confined compressive strength, strain modulus and critical stress intensity factor (or fracture toughness). These are treated in turn in Section 5.0 with a comparison of urea model ice and the appropriately scaled sea ice values. In all respects, this new ice — termed EG/AD/S model ice — is superior to any existing type of model ice.

2.0 GROWTH OF SOLIDS FROM IMPURE MELTS

In growing model ice, it is well known that it is necessary to incorporate a low molecular weight dopant in the ice (to date this has been sodium chloride or urea) in order to be able to reduce the strength of the ice for the model test. This is accomplished by
internal melting of the ice based on maintaining equilibrium defined by the phase diagram of the ice–water–chemical system. In the natural growth process of the ice however, the chemical dopant is not trapped in the ice sheet at a uniform rate and this leads to a highly non-uniform distribution of dopant particles with depth in the ice. For a single dopant system the ice has few dopant particles trapped in the upper layer. This produces a mechanically hard upper layer. Because the dopant particles are mostly rejected from the growing ice, they build up at the growth interface until sufficient concentration exists to bring about an instability due to “constitutional supercooling”, i.e. supercooling due to composition (Tiller et al., 1953). In this region a high concentration of dopant particles are trapped. Below this, the ice structure is dendritic and stable for the rest of the ice growth. Thus, as seen in Fig. 1, the ice sheet consists of an upper mechanically hard layer (A), a thin transition layer of high dopant concentration (B), and a lower, mechanically weak dendritic layer (C). This structure of ice is produced for growth from any single dopant system and is a consequence of the natural growth of ice from aqueous solutions. Since the mechanical properties of the ice are controlled by its structure, this three layer system produces incorrect scaling of some ice properties, and through separation of the top and lower layers, the potential for an unrealistic failure mode. Clearly, in order to produce a model ice which does not have this three-layered system, it is necessary to be able to grow the ice such that it has a uniform distribution of dopant particles with depth. If this could be done, it would be possible to produce a single-layered, columnar-structured ice. In searching for clues to do this, it is informative to consider both the theory of solids grown from impure melts from the metallurgical field (Chalmers, 1964), and to review past experimental results of ice grown from doped solutions.

Fig. 1. Vertical thin section of urea model ice showing: A – mechanically hard upper layer; B – transition layer; C – lower dendritic layer. The grid is 1 cm on a side.
Equilibrium between a crystalline solid and a liquid is represented on a binary equilibrium diagram by two lines (see Fig. 2): the liquidus line, above which the liquid is the stable phase, and the solidus line, below which the solid is stable. The fact that the two do not coincide indicates that the solid usually differs in composition from the liquid in equilibrium with it. This is expressed through an equilibrium solute distribution coefficient, \( k_0 \), where

\[
k_0 = \frac{C_S}{C_L}
\]  

(1)

where \( C_S \) and \( C_L \) are the concentrations of the solid and liquid in equilibrium respectively. For the case of solidification of ice from a doped solution, \( k_0 \) is very small \((\approx 10^{-4})\), Harrison and Tiller (1963) and less than one, so the solute particles are rejected from the ice sheet.

Consider, for example, a water solution containing a chemical dopant with a concentration of \( C_0 \). The first layer of ice to freeze will have a solute concentration of \( k_0 C_0 \). As the solidification proceeds, the concentration in the liquid adjacent to the ice will increase because the dopant is being rejected from the interface. This will result in an increase in the impurity content in the ice until a steady state condition is reached. At this stage, the impurity distribution will be as shown in Fig. 3. If the removal of the dopant particles from the interface is controlled by diffusion processes, the amount of solute rejected at the interface is just balanced by the amount diffusing away from it. At steady state, the sum must be zero, and the governing equation is given by (Chalmers, 1964)

\[
D \frac{d^2C}{dz^2} + R \frac{dC}{dz} = 0
\]  

(2)

where \( C \) is the concentration, \( z \) is the distance in the growth direction, \( D \) is the diffusion coefficient and \( R \) is rate of ice growth. This equation has been solved for ice grown from doped water solutions by Weeks (1967). His calculations showed that for this system, diffusion is not the controlling process; free convection of the dopant particles must also be considered. This was done by Weeks and Lofgren (1967) by using the approach of Burton, Prim and Slichter (1953), defining an effective solute distribution coefficient, \( k_e \) as

\[
k_e = \frac{C_S}{C_0}
\]  

(3)

where \( C_S \) is the concentration of the solid that is formed at a certain instant by solidification of a liquid, of average concentration \( C_0 \). The value of \( k_e \) depends on the conditions under which solidification takes place, whereas \( k_0 \) is a characteristic of the system. For example, for sea ice grown from sea water of 35% salinity, an ice salinity of 5% is typical, so \( k_e = 5/35 = 0.14 \). For model ice, the effective distribution coefficient for the whole ice thickness (or bulk distribution coefficient \( k_b \)) is typically 0.3–0.4 depending upon the ice thickness and growth conditions (Timco, 1981b). The use of this approach...
has the advantage that the mathematical formulations derived for the case of diffusion only can still be used by replacing \( k_0 \) by \( k_e \). Then, the visualization of the process as shown in Fig. 3 is still applicable. From this figure and the present discussion, it is easy to see that as the effective solute distribution coefficient approaches one, the solute distribution in the ice becomes much more uniform such that for \( k_e = 1, k_e = k_b, \) and a uniform single-layered ice sheet will result.

The question then is: "How can the distribution coefficient of a water-dopant system be increased?". It is known that although increasing the rate of growth of the ice traps comparatively more dopant in the ice (Weeks and Lofgren, 1967), this mechanism alone does not bring about the desired result. In some tests on sodium chloride doped ice, Timco (1978) found that the bulk distribution coefficient \( k_b \) for the ice could be increased significantly by the addition of a relatively small amount of detergent (in these tests dodecyl sodium sulphate) - see Fig. 4. This appears to be a promising approach to the problem. Although the mechanism for the increase in \( k_b \) is not known, it seems that the detergent, being a surfactant or surface-active agent, breaks down the surface tension of the water, thereby allowing more dopant particles at the growth interface. For a given growth rate, this results in more dopant being trapped in the ice. Moreover, since the surface tension of the solution influences the width \( (a_0) \) and separation \( (\delta) \) of the individual dendritic platelets at the bottom of a growing ice sheet (see Fig. 5), a decrease in the surface tension should produce thinner platelets and allow for more (or larger) impurity pockets in the ice. This also would serve to increase the effective distribution coefficient. In any event, it seems that the addition of a surface-active agent to the melt should help to produce the desired results.

In reviewing the test results of various investigators on growth of ice from impure melts (for example, Moesveld, 1937; Pounder, 1958; Timco, 1981b) a feature common to all is the finding that the addition of a long chain organic molecule to the melt helps to produce a reduction in strength of the ice. It was found that the large molecules assisted in strength reduction by inhibiting the growth of large ice crystals. It seems that the large molecules at the growth interface would restrict lateral platelet growth and thereby force the platelets to remain small and grow vertically. This should produce a fine-grained, columnar ice. Since the fracturing process is frequently along grain boundaries, a large number of small crystals results in a structurally weaker ice. These test results, therefore, suggest that a third type of chemical should be added to the melt - namely a long chain organic molecule.
In summarizing this section, it is seen that there are three different types of chemicals which must be added to the melt in order to produce the desired structure and strength characteristics for the model ice. These are:

1. A low molecular weight dopant which is trapped in the ice as impurity pockets and, through maintenance of system equilibrium, reduce the strength of the ice by internal (eutectic) melting.

2. A surface-active agent, or surfactant, which reduces the surface tension of the solution thereby allowing more of the low molecular weight dopant to be trapped in the ice. At sufficient concentrations, this should produce a single-layer, columnar-structured ice.

3. A long chain organic molecule of high molecular weight to inhibit the lateral growth of the individual ice platelets in the sheet. This helps to produce a fine-grained ice.

Overall, each of these chemicals performs a different, yet vital role in the growth of the ice.

3.0 THE CHOICE OF SUITABLE DOPANTS

Having established the types of chemicals which must be in the solution to produce the desired model ice, it is necessary to pick suitable candidates for each. In addition to the criterion defined above, each chemical must be non-toxic, non-irritating, soluble in cold water, non-volatile, non-corrosive, biodegradable or non-polluting (when discarded) and relatively economical to use. Clearly, each chemical must have the right combination of properties.

For the low molecular weight dopant, there are a number of possible candidates including sodium chloride, urea, lithium chloride, etc. Each of these would have various advantages and disadvantages. In selecting a suitable candidate, it would be wise to choose one which has a high bulk solute distribution coefficient in ice. In a series of tests on growth of ice from impure melts, Timco (1981b) measured the bulk distribution coefficient for a number of water-dopant systems and these can be used for guidance. The highest distribution coefficients were measured for the R-OH series of alcohols (where R is the alkyl radical) such as CH₃OH methyl alcohol; C₂H₅-OH ethyl alcohol; C₃H₇-OH propyl alcohol. These, however, must be ruled out because they produce incorrect density scaling (Shulhan et al., 1978). The next highest distribution coefficients were measured for the polyhydric alcohols (HOCH₂ CH₂-OH ethylene glycol; CH₃CH(OH) CH₂-OH propylene glycol). These are attractive candidates for the low molecular weight dopant. Since ethylene glycol is less expensive than the other chemicals in this series and it meets all of the stated criteria, it appears to be a suitable choice. Thus, ethylene glycol (EG) was chosen as the low molecular weight dopant.

The choice of a suitable surfactant is more complicated since there has been very little work done in this area. In addition to the other criteria of non-toxicity, etc., it must be a good wetting agent with high detergency power, yet have extremely low sudsing. The detergent originally used by Timco (1978) – dodecyl sodium sulphate – would not be suitable since it is a very high sudsing detergent, and management of the suds in an ice tank (which would be produced through air bubbling or any type of agitation) would be an onerous task. Recently, however, a number of detergents which meet all of the stated criteria have become available from several different chemical companies. These detergents were developed for automatic dishwashing machines where high detergency but very low sudsing is a necessity. These detergents, which are aliphatic (i.e. based on animal or plant fats or oils), are biodegradable, liquid, non-ionic surfactants. Thus, as a means to reduce the surface tension in the solution, an aliphatic detergent (AD) was chosen. After consultation with a number of chemical companies, Rexonic P-1 was obtained for the test program from the Hart Chemical Company of Guelph, Ontario, Canada.

The choice of a suitable candidate to use as the high molecular weight dopant is also not straightforward since very little research has been done in this area. Potential candidates which were considered include sodium stearate and sodium carboxymethyl cellulose. (The latter is used in ice cream to inhibit large crystal growth and thereby give it a smooth texture.) Tests with these chemicals however, indicated that they were difficult to mix homogeneously into a cold solution. Much more work could be performed in this area to look at other
suitable candidates. At this stage however, it was decided simply to choose a high molecular weight substance which met all of the requirements and was inexpensive. Thus, sucrose or sugar (S) which has a molecular weight of $\approx 340$ was chosen as the high molecular weight dopant.

In summarizing this section, the choice of the three dopants are: ethylene glycol (EG), aliphatic detergent (AD) and sugar (S). Based on this, it is convenient to call the ice EG/AD/S model ice. With this formulation, the relative concentrations of each of the chemicals in the solution can be described in a systematic way.

4.0 DEVELOPMENT OF THE MODEL ICE

The ice was grown in the ice tank in the Hydraulics Laboratory at N.R.C. in Ottawa (Pratte and Timco, 1981). The tank is 21 m long $\times$ 7 m wide $\times$ 1.2 m deep, large enough to ensure that any edge or bottom effects are minimal. Before growing the ice, each of the chemicals was added to the tank water in appropriate concentration by weight. The general procedure for producing the model ice was the same as that used for growing urea model ice. The whole solution was pre-cooled at an ambient air temperature of $-18^\circ$C while it was being continually agitated with an air bubbler system. When the whole solution reached a temperature of $0.1^\circ$C above its freezing point, the bubbler system was shut off, the ice skin which had formed cleared away, and the solution nucleated using a “wet-seeding” process (see Pratte and Timco, 1981 for more detail). The ice was grown at an ambient air temperature of $-18^\circ$C for 14½ hours. This produced an ice sheet 4 cm thick. At that time, the room was allowed to warm up to $+2^\circ$C and the ice tempered at that temperature. This tempering process warms the ice sheet and aids in reducing its strength.

Since there are three different chemicals in the solution, there are, in effect, three independent variables which can be adjusted to optimize the properties of the ice. As such, in developing the ice,

Fig. 6. Vertical thin section of EG/AD/S ice showing the strictly columnar, single-layer structure of the ice. The grid is 1 cm on a side.
each was varied independently until the desired ice properties were obtained. Because of the large number of ice sheets which were grown in the development process, the full details cannot be presented here. Instead, the detailed results for one set of concentrations will be presented. For the present ice basin which has an ice growth rate of 2.8 mm/h at -18°C using forced convection, it was found that a model ice grown from a solution with concentrations of the three chemicals of 0.46/0.032/0.049% gave a model ice which had the same strength/warm-up characteristics as 0.6% urea ice (i.e. the strength was reduced during the tempering process at the same rate as urea ice). This concentration of urea gave optimal ice properties for this ice tank. Thus, this makes a comparison of the properties of the new model ice with those of urea ice valid for this particular tank.

It should be mentioned that the concentration of chemicals of 0.46/0.032/0.049% may not be the optimum one for all ice tanks. Just as the concentration of urea required to give optimum properties was found to be different in the various ice modelling basins (0.6% N.R.C. Hydraulics, Timco, 1984a; 0.95% CRREL, Hirayama, 1983a, 1983b; 0.8% HSVA, Schwarz, personal communication; 1.0% NKK, Sudo et al., 1983; 1.0% I.I.H.R., Kitazawa and Ettema, 1984), the concentrations for the EG/AD/S ice will have to be adjusted accordingly. The use of three chemicals will add to the complexity of doing this. The results from the urea ice, however, may be able to serve as a guideline in the selection process. Since the amount of urea necessary for optimum behaviour was related to the growth rate of the ice (such that less was required for the higher growth rates), it seems reasonable to assume that the same behaviour would occur for this new ice. Thus, as a first estimate of the concentrations, it is reasonable to compare the relative concentrations of the low molecular weight dopant in the mix. For the present tank, 0.46% ethylene glycol was used compared to 0.6% urea, giving a ratio of 0.77. Using this

Fig. 7. Horizontal thin section of EG/AD/S ice taken at a depth of 2 cm showing the fine grain size and the impurity pockets in the ice. The grid is 1 cm on a side.
value, for example, for the CRREL tank which had an optimum urea concentration of 0.95%, a first estimate for the ethylene glycol concentration is 
\((0.77)(0.95) = 0.71\%\). If the other two chemicals remain in the same ratio as in the present tank, then the required concentration for the CRREL tank would be 
\(0.73/0.051/0.078\%\). Once more information is obtained by other tanks using this formulation, the selection process for the chemical concentrations will certainly be refined.

The structure of the EG/AD/S model ice grown in the present tests is shown in Figs. 6 and 7 for vertical and horizontal directions. The figures show photographs of thin sections of the ice observed through crossed-polaroids. The grid is 1 cm on a side. In examining these photographs it is evident that the ice is single-layered, fine-grained and columnar. Thus, from a structural point of view, this ice possesses all the desired properties.

5.0 MECHANICAL PROPERTIES OF THE ICE

Since the structure of the ice directly controls the mechanical properties, it is of interest to measure the mechanical properties and compare them to the appropriately scaled prototype sea ice values. This comparison is necessary in order to evaluate the suitability and accuracy of this new model ice as a representation of columnar sea ice. To this end, a series of mechanical property tests were undertaken. The tests included measurements of the flexural strength, uni-axial and confined compressive strength, strain modulus and critical stress intensity factor. In this section, the results and comparison of these tests are presented. Since this is a very wide ranging task, each part of this section will be presented in a systematic way as follows:

(1) First, review sea ice properties to obtain representative prototype values. Then, by applying the appropriate scale factor, determine the value or range of values and behaviour which the model ice should have.

(2) Next, describe the test procedures used for measuring the particular property of the model ice. Since the ice is anisotropic, tests were performed for various loading directions and loading rates. For this, the reference system shown in Fig. 8 was used.

(3) Finally, present the results on the model ice and compare them to both the scaled sea ice values and the corresponding values for urea model ice as taken from the literature.

5.1 Flexural strength

The flexural strength of ice is not a basic material property. Since any flexural test creates a non-uniform stress distribution in the ice, assumptions are required about the ice properties in order to interpret the test results. The flexural strength, therefore, is generally considered to be an index test. In spite of this, there have been several investigations of the flexural strength of ice (Weeks and Anderson, 1958; Brown, 1963; Dykins, 1968; Airaksinen, 1974; Tabata et al., 1975; Vaudrey, 1977; Frederking and Häusler, 1978; Gow et al., 1978), and this property has developed great significance for model testing in ice. Figure 9 shows a compilation of test results for both sea ice and freshwater lake ice using large
beam samples in both cantilever and simple beam loading arrangements. Although the scatter is considerable, the trend shows flexural strength values which decrease from ≈1.2 MPa down to 0.2 MPa as the brine volume in the ice increases. As seen in this figure, for sea ice, there is no significant difference in strength as measured using either the cantilever or simple beam approach. For freshwater ice, on the other hand, there is an apparent difference such that the simple beam approach gives higher values. The reason for this is not known, although this difference has been attributed to a stress concentration at the root of the beam (see Schwarz and Weeks, 1977; Gow et al., 1978; Timco, 1985). With regard to loading rate, both Tabata et al. (1967) and Määtäinen (1975) report that the flexural strength increases with increasing stress rate, although Määtäinen (1975) shows that if a correction factor is included to compensate for the inertial forces of the beam mass and the hydrodynamic water forces, this rate-dependence disappears. Other tests by Kayo et al. (1983) and Timco and Frederking (1982, 1983a) indicate no strong loading rate effects. For both sea ice and freshwater ice, when loaded to failure, the load—time curve exhibits an abrupt drop at yield, indicating brittle-type failure. With regard to loading direction, tests by Weeks and Anderson (1958), Tabata et al. (1967) and Kayo et al. (1983) have indicated that the flexural strength of sea ice does not depend upon whether the top or bottom of the ice sheet is placed in tension. Tests on freshwater ice, on the other hand, indicate that the flexural strength is significantly higher when the top is loaded in tension (Gow et al., 1978).

It appears that the flexural strength of sea ice is relatively insensitive to test technique, loading rate and loading direction. It is, however, a function of brine volume which itself is a function of temperature and salinity. Because of this, it is necessary to generalize the results into two different cases which are of interest to model tank operators in order to arrive at representative values of flexural strength for scaling purposes. These are: (1) mid-winter sea ice (i.e. very cold ice), and (2) early spring ice (i.e. warmer sea ice). To arrive at appropriate values of flexural strength for these two cases, it is necessary to know the brine volume in the ice for both cases. The brine volume can be calculated by using the relationships derived by Cox and Weeks (1982) if the salinity, temperature and density of the ice are known. Having established this, appropriate strength values can be inferred from Fig. 9. For mid-winter ice, the air temperature in the Arctic can reach -45°C. With no snow cover, there is a linear temperature gradient in the ice with a resulting average ice temperature of -21°C. For a typical first-year ice sheet with a salinity of 4–5%/o (Cox and Weeks, 1974), this represents an average brine volume of 12%/o (v_b^½ = 0.11). For warmer sea ice, average temperatures of -3°C to -5°C may be appropriate, and with salinities of 4–5%/o, the brine volume in the ice is 40–80%/o (v_b^½ = 0.20–0.28). For these brine volumes in Fig. 9, appropriate flexural strength values are 0.8 MPa for cold sea ice and 0.5 MPa for warm sea ice (see Timco, 1985 for a more detailed analysis). These representative values can be used for scaling purposes.

In the present tests, the flexural strength was measured using both the cantilever beam and simple beam loading arrangement. The beams were cut carefully from the ice using a hand (pruning) saw. Since it is known that the apparent flexural strength of model ice depends upon beam dimensions (Tatinclaux and Hirayama, 1982), the beam dimensions in both cases were standardized such that the length of the beam (L) was five to six times the ice thickness (h), and the width of the beam (w) was twice the ice thickness (Timco, 1981a). The beams were loaded to failure (at load P) and the flexural strength (σ_F) was determined using linear elastic beam theory from σ_F = 6 PL/wh^2 for the cantilever beams, and σ_F = 3 PL/2wh^2 for the 3-point or simple beam (where L is the spacing between outer supports in the latter case). Rate and anisotropy effects were investigated by varying the loading time and direction respectively. It should be noted that unless otherwise specified, the flexural strength refers to the strength of the ice measured using the cantilever beam technique by downward loading of the beam (i.e. putting the top of the beam in tension).

For modelling purposes, where the scaling laws are usually based on Froude and Cauchy laws (see e.g. Timco, 1984a), the flexural strength of the ice should be reduced by the linear scale factor (λ) for the test. From this, for most model tests using model ice, the conventional practice has been to define the
scale factor in terms of both the linear geometric scale factor (\( \lambda = \text{linear dimension in prototype divided by the linear dimension in the model} \)) and the flexural strength of the ice. To achieve the desired strength in the model regime, the ice is warmed up at a constant room temperature, and through maintenance of the ice–water–chemical phase system, the strength of the ice decreases. As shown in Fig. 10, the flexural strength can be altered over a wide range (from 100 kPa to 20 kPa). This represents scale factors ranging from 8 to 40 for cold sea ice and 5 to 25 for warm sea ice. As such, it is evident that there is no problem in attaining appropriately scaled flexural strength values for EG/AD/S ice over a wide range of scale factors.

Figure 11 shows a comparison of the flexural strength of EG/AD/S model ice measured using either the cantilever or simple beam techniques. Over the whole range of model ice strengths, there is no significant difference between the two. This behaviour is also observed for urea model ice (Timco, 1985), and is in agreement with the results for sea ice.

Figure 12 shows the flexural strength versus both the average stress rate (defined as the strength divided by the time to failure) and the nominal loading time for EG/AD/S ice. Over the limited range of loading rates (and times) associated with model tests, there is no strong loading rate effect. This was also found for urea model ice (Timco, 1985). This is in agreement with test results for sea ice and indicates that the flexural strength of EG/AD/S model ice scales correctly with regard to rate effects.

Figure 13 shows a typical load–time curve for both EG/AD/S ice and urea model ice. From this figure, it is evident that for EG/AD/S ice, the load drops abruptly to zero at failure indicating a brittle-type failure. This behaviour is similar to that found for sea ice, but considerably different than that observed for a multi-layered model ice. In this latter case, there is not an abrupt drop at failure — instead, the load decreases slowly to zero after the initial failure (Enkvist, 1972; Schwarz, 1975; Timco, 1983b). This remnant load, which is independent of the strength of the ice, represents extra energy which
is not found in the prototype system. Since this is not observed with EG/AD/S ice, it is clear that this ice not only correctly scales the prototype behaviour, but it also is superior to urea model ice in this regard.

Figure 14 shows the flexural strength measured by pulling up on the beam (i.e. placing the bottom of the ice sheet in tension) versus the flexural strength measured by pushing down on the beam (i.e. placing the top of the ice sheet in tension). The test results for both EG/AD/S and urea model ice are shown. The figure clearly shows that the flexural strength of EG/AD/S ice is much less sensitive to loading direction than urea ice. Defining a homogeneity factor as \( H = \frac{\sigma_F(t)}{\sigma_F(I)} \), it is seen that for these tests \( H = 0.69 \) for EG/AD/S ice and \( H = 0.39 \) for urea ice (for ice of 4 cm thickness). For sea ice, there is no apparent strength dependence with loading direction, so \( H = 1.0 \). It is clear that EG/AD/S ice is a much better representation of sea ice than urea ice in this respect. Although not the same as sea ice, EG/AD/S ice offers a significant (≈75%) improvement over conventional urea ice. This improvement reflects the single-layer structure of EG/AD/S ice.

In summarizing the flexural behaviour, it is seen that the flexural strength of EG/AD/S ice can be altered over a wide range of scale factors, and scales properly with regard to test technique, loading rate, load–time behaviour, and loading direction. In the latter two, EG/AD/S ice offers a significant improvement over urea model ice.

**5.2 Uni-axial compressive strength**

The uni-axial compressive strength of ice is an important property because it controls the stress level at which the ice will crush. It has significant implications when viewed in terms of ice loads on offshore structures or icebreaking vessels. To date, there have been a number of investigations of the uni-axial compressive strength of both freshwater ice (Hawkes and Mellor, 1972; Sinha, 1981) and sea ice (Peyton, 1966; Schwarz, 1983; Wang, 1979; Sinha, 1983, 1984; Frederking and Timco, 1983, 1984). In general, the compressive strength of the ice has been found to be a function of the strain rate, loading stress rate, loading direction, temperature, salinity and density. Because of the complexity of ice and the large number of parameters which affect its strength, a direct comparison of the results from all investigators is not possible. Recently, however, Nadreau and Michel (1984) compared the results of tests by several investigators for both
freshwater ice and sea ice. They found that for horizontally-loaded specimens, the yield strength increases with strain rate with ductile-type failures up to a maximum for a strain rate around \(10^{-3}\) s\(^{-1}\). For higher strain rates up to \(10^{-2}\) s\(^{-1}\), a transition zone occurs. For strain rates above \(10^{-2}\) s\(^{-1}\), the ice failure is brittle in nature and the strength values generally decrease with increasing loading rate. This behaviour therefore produces a “hump” in the strength–strain rate variation for ice. In the low loading range where ductile failure occurs, the rate dependence of the strength of freshwater ice at \(-10^\circ\text{C}\) is given by (Sinha, 1981)

\[
\sigma = 210 (\dot{\varepsilon})^{0.34}
\]

where \(\sigma\) is in MPa and \(\dot{\varepsilon}\) is in s\(^{-1}\). For sea ice, Timco and Frederking (1985) have recently compared the test results from a number of investigations in several locations in the Canadian Arctic and found that the strength of sea ice in the ductile loading range \((10^{-5} \leq \dot{\varepsilon} \leq 10^{-3}\) s\(^{-1}\)) is given by

\[
\sigma = 47 (\dot{\varepsilon})^{0.26} \left(1 - \sqrt{\frac{\nu_T}{320}}\right)
\]

for horizontally-loaded ice, and

\[
\sigma = 168 (\dot{\varepsilon})^{0.22} \left(1 - \sqrt{\frac{\nu_T}{280}}\right)
\]

for vertically-loaded ice, where \(\sigma\) is in MPa, \(\dot{\varepsilon}\) is in s\(^{-1}\) and \(\nu_T\), which is the total (brine + air) porosity, is in parts per thousand. With regard to stress-rate, similar equations were found, such that

\[
\sigma = 8.4 (\dot{\sigma})^{0.22} \left(1 - \sqrt{\frac{\nu_T}{320}}\right)
\]

and

\[
\sigma = 32.6 (\dot{\sigma})^{0.22} \left(1 - \sqrt{\frac{\nu_T}{280}}\right)
\]

for horizontally-loaded and vertically-loaded samples respectively where \(\sigma\) is in MPa and \(\dot{\sigma}\) is in MPa s\(^{-1}\). These equations relate the uni-axial compressive strength of columnar sea ice explicitly in terms of loading direction, loading rate and total porosity of the ice, and implicitly in terms of the salinity, temperature and density. The equations show that the vertically-loaded strength is of the order of 3.6 to 3.9 times higher than the horizontally-loaded strength for comparable conditions. These equations will be used as a basis for comparison with the results of the model ice tests.

In testing the uni-axial compressive strength of model ice, the mechanically weak nature of the ice presents several unique problems which influence the type of test which can be done (Timco, 1981a). These problems include the necessity for quickly testing the ice once it is removed from the solution (to minimize the liquid drainage from the ice), the difficulty in choosing a suitable plate material, the necessity of having two different types of test apparatus to cover the whole range of loading rates applicable to model tests, and the necessity of studying the ice with two loading directions (since the ice is anisotropic). In testing the ice, a cantilever beam was cut in the ice sheet and the flexural strength was measured. The beam was then immediately cut into a standard size piece \(3.6 \times 3.6 \times 10\) cm on a band saw and tested in the compression tester. This procedure allowed a direct comparison of the uni-axial compressive strength of the ice with its flexural strength. The standard size for the ice was chosen since it gives a 3:1 aspect ratio and the thickness of 3.6 cm is in the range commonly used in model tests.

Two different types of test apparatus were used to measure the strength at different loading rates. To simulate a slow moving ice sheet interacting with a stationary structure, a conventional compression test apparatus was used. For a model test involving an ice-
breaker moving through an ice sheet, relatively high loading rates are encountered, and to simulate this, a lever-type compression tester was used (Timco, 1980).

Figures 15 and 16 show the horizontally loaded uni-axial compressive strength as a function of nominal strain rate and average stress rate respectively at a flexural strength value of 55 kPa. In perfect agreement with the results from freshwater ice and sea ice, the strength exhibits a maximum value at a strain rate of \( \approx 10^{-3} \text{s}^{-1} \). In addition, the strength shows a definite stress rate dependence in agreement with that found for sea ice. As such, EG/AD/S ice scales the rate dependence of prototype ice extremely well. It should be noted that this rate dependence was not observed for urea model ice. Instead, urea model ice was found to be rate independent over the range of loading rates encountered in model tests (Timco, 1983a). As such, the EG/AD/S ice correctly scales the prototype ice behaviour and is far superior to urea model ice in this respect.

Figure 17 shows the compressive strength for EG/AD/S ice for horizontal loading at a strain rate of \( 1 \times 10^{-3} \text{s}^{-1} \) (i.e. at the strain rate where the maximum value occurs). Included on this figure are the results for urea model ice. There is good agreement between the two. In general, the uni-axial compressive strength decreases with decreasing flexural strength (or increasing scale factor).

To check on the accuracy of scaling of the compressive strength, it is necessary to examine each model test configuration individually and evaluate the appropriate strength values. In the present analysis a typical prototype situation will be chosen. For example, if the loads on an artificial island in a slowly moving ice field were being studied, the prototype strain rate would be \( \dot{\varepsilon} \approx \frac{v}{2D} \) where \( v \) is the rate of ice movement and \( D \) is the diameter of the island (Ralston, 1979). For \( v = 3.0 \text{m h}^{-1} \) and \( D = 80 \text{m} \), the strain rate would be \( \dot{\varepsilon} = 5.2 \times 10^{-6} \text{s}^{-1} \). Using eqn. (5) for the sea ice compressive strength and assuming an ice salinity of 5%, an average temperature of \(-20^\circ\text{C} \) and a density of 0.9 g cm\(^{-3} \), then \( \nu_T = 43\% \) and the prototype compressive strength for horizontal loading would be \( \sigma = 30 (\dot{\varepsilon})^{0.26} \). At a strain rate of \( 5.2 \times 10^{-6} \text{s}^{-1} \) the strength would be 1.3 MPa. If the model test was performed at a scale factor of 30 (say), then the model scale value for compressive strength should be \( \approx 43 \text{kPa} \). Basing the scale factor on the flexural strength for cold sea ice, the model flexural strength should be
27 kPa for $\lambda = 30$. At this flexural strength the uni-
axial compressive strength is $\approx 70$ kPa from Fig. 17.
As such, although the uni-axial compressive strength of
the model ice is slightly high, there is reasonable
scaling of the uni-axial compressive strength in this
case. It should be remembered, however, that the
values of the compressive strength from Fig. 17
were generated at the strain rate which produces
the maximum strength value. As such it should be
possible to reduce the strength of the ice to the
correct value by simply choosing the appropriate
strain rate in the model test. This type of an analysis
should be done in all model tests to check the ac-
curacy of scaling of the compressive strength.

Figure 18 shows the uni-axial compressive strength
for vertically-loaded samples versus the flexural
strength of the ice. In this case, only high loading
rate tests were performed using the lever-type com-
pression tester. Included on this figure are the corre-
spending tests on urea model ice. There is good
agreement between the two. For comparable (high)
loading rates it was found that the vertically-loaded
compressive strength was on the order of three times
higher than the horizontally-loaded compressive
strength when compared at the same flexural
strength. This is in good agreement with that found
for sea ice. This anisotropy for the EG/AD/S ice
reflects its columnar structure and this allows it to
correctly scale this behaviour. It should be noted
that this cannot be done by any granular-structured
ice.

In summary, it appears that the uni-axial com-
pressive strength for EG/AD/S ice scales correctly
from sea ice values with respect to strength values,
rate effects and anisotropy effects. In its rate depen-
dence, it is far superior to urea model ice.

5.3 Confined compressive strength: the failure
envelope

When ice interacts with a structure, it can ex-
perience a complex stress field. Since the response of
ice cannot be described uniquely by the uni-axial
stress properties of the ice in this case, it is important
to have some knowledge of the behaviour of ice
under complex stress states. One way in which this
has been done is by performing confined compression
tests. In these tests, the material is loaded in one
direction while confined in a second direction. By
loading the ice using different orientations, the failure
stresses can be determined for various combinations
of stress states. For horizontal loading, confinement
is possible on either the sides of the sample (A-type)
or on the top and bottom of the sample (B-type) —
see Fig. 19. To date, tests of this type have been done

![Fig. 18. Uni-axial compressive strength with vertical loading versus flexural strength for both urea and EG/AD/S model ice.](image1)

![Fig. 19. Schematic showing A-type and B-type confinement for the confined compression tests.](image2)
on freshwater ice by Frederking (1977) and Croasdale et al. (1977), on sea ice by Timco and Frederking (1983b, 1984, 1985) and Blanchet and Hamza (1983), and on urea model ice by Timco (1983a). The results of the tests on columnar-grained freshwater ice and sea ice indicate that the strength of the ice with A-type confinement is typically three to four times higher than the uni-axial compressive strength measured under the same conditions. On the other hand, the results of the B-type confinement are virtually identical to the uni-axial compressive strength. The reason for this behaviour has been explained in terms of basal-plane glide in the ice (see Frederking, 1977). The results of these tests are usually presented in the form of a "failure envelope" for the ice. This is a description of the stress levels at which the ice yields for any combination of compressive or tensile stress states. The procedure for doing this has been discussed by Ralston (1977). The failure envelope determined for columnar-grained sea ice by Timco and Frederking (1985) is shown in Fig. 20 for both the x-y plane and the x-z plane (normalized with respect to the horizontally-loaded uni-axial compressive strength of the ice $C_x$). For columnar sea ice, the failure envelope "balloons-out" into the compression-compression quadrant in the horizontal (x-y) plane such that stresses up to four times the uni-axial compressive strength of the ice can be generated before ice failure. In the x-z plane (i.e. in the vertical plane), the long, thin shape of the envelope reflects the fact that the unconfined compressive strength in the vertical (z) direction is three and a half to four times the uni-axial compressive strength in the horizontal (x) direction. The size and shape of the full failure envelope should be properly scaled in order to have reliable results in the model regime.

In performing these tests on the model ice, a sub-press was built with two parallel confining walls which restrict the ice deformation in that direction. The inside of the sub-press was lined with bakelite to reduce the friction on the side walls. In testing, a cantilever beam was cut in the ice sheet and the flexural strength was measured. Then, the ice sample was removed from the solution and quickly and carefully cut to size on a band saw so that there was a tight fit in the sub-press (sample size 3.6 × 3.6 × 10 cm). The sample was then loaded using a conventional compression test machine at a nominal strain rate of $1 \times 10^{-3} \text{ s}^{-1}$. Both A-type and B-type confinement tests were performed by simply altering the orientation of the ice piece in the sub-press. A number of tests were performed covering a wide range of flexural strengths (i.e. scale factors).

The results of the tests are shown in Fig. 21 for both the urea model ice (from Timco, 1983a) and EG/AD/S ice. There is a striking difference in the results between the two. For urea model ice, the strength of the ice with A-type confinement was typically twice that of the uni-axial compressive strength of the ice, whereas the strength with B-type confinement was one and a half times higher than the uni-axial compressive strength. This behaviour for the confined compressive strength of the urea ice does not accurately scale the behaviour of sea

![Fig. 20. Failure envelopes for columnar sea ice, EG/AD/S model ice and urea model ice showing the excellent agreement between the EG/AD/S ice and sea ice.](image)

![Fig. 21. Confined compressive strength with A-type and B-type confinement for both urea ice and EG/AD/S ice. For sea ice, the strength with A-type confinement is four times the uni-axial strength, whereas the strength with B-type confinement is the same as the uni-axial strength. Thus, there is excellent agreement between EG/AD/S ice and sea ice.](image)
ice. This comes about because of the layered structure of the urea ice whereby a physical “splitting” of the ice takes place between the top and bottom layer (see Fig. 1). This is an additional and unrealistic failure mode in urea model ice which is not found for sea ice. The results for the EG/AD/S ice, on the other hand, do not show any evidence of this failure mode. The strength of the ice with A-type confinement is typically four times the uni-axial compressive strength. With B-type confinement, the strength is virtually identical to the uni-axial strength. This is in perfect agreement with that found for columnar sea ice.

Using the results of these tests, the failure envelopes for both urea ice and EG/AD/S ice can be outlined. These are shown in Fig. 20 along with the failure envelope for columnar sea ice. In comparing the three, it is clear that the single-layered EG/AD/S ice very accurately scales this sea ice behaviour, and in this respect EG/AD/S ice is far superior to urea ice. It should be noted that for a granular-structured model ice, a proper fit of the failure envelope is impossible. In this case, the failure envelope would be represented by a circle through the $(\pm 1, \mp i)$ points on each axis. As such, this type of ice would fail long before the high stresses which can occur in columnar-structured ice could be generated. Thus, a granular-structured ice would underpredict the ice loads in this case. This emphasizes the necessity of having a columnar-structured model ice.

5.4 Strain (elastic) modulus

The strain or elastic modulus ($E$) is a measure of the relative stiffness of the ice sheet and, for model tests, it is usually discussed in terms of the $E/\sigma_F$ ratio. For sea ice, there have been a number of measurements of the modulus using dynamic techniques such as ultrasonic tests (Langleben and Pounder, 1963) or seismic tests (Anderson, 1958), and using static techniques on ice beams (Dykins, 1971; Vaudrey, 1977). In general there is good agreement with the results showing a general tendency of decreasing modulus with increasing brine volume. Vaudrey (1977) found a linear decrease in the modulus with the square root of the brine volume such that $E = 5.3 - 13\sqrt{\nu_b} \text{ GPa}$ where $\nu_b$ is the brine volume fraction. Using this relationship and assuming representative values of temperature and salinity for cold sea ice of $-20^\circ \text{C}$ and $5\%_\text{o}$ respectively, a brine volume fraction of $0.016$ is obtained and the corresponding modulus is $3.7 \text{ GPa}$. Based on Froude and Cauchy scaling laws, the modulus should scale by the linear scale factor $\lambda$, so the $E/\sigma_F$ ratio should be the same in model and prototype. For cold sea ice, an average $E/\sigma_F$ ratio is on the order of $(3700/0.8) = 4600$. For warm sea ice, using $S = 5\%_\text{o}$ and $T = -3^\circ \text{C}$, the brine volume fraction is $0.078$ and $E = 1.7 \text{ GPa}$. Then, for warm sea ice, a typical $E/\sigma_F$ ratio is $(1700/0.5) = 3400$. These represent average $E/\sigma_F$ ratios for sea ice. A more detailed analysis by Schwarz (1975) has indicated that the range of $E/\sigma_F$ ratios in nature is $2,000--8,000$. These values can be used for scaling purposes for model tests.

In measuring the strain modulus for the model ice, the procedure detailed by Sodhi et al. (1982) was used. This technique is based on the measurement of the deflection of the ice sheet loaded in discrete increments, with care being taken to separate out the elastic and inelastic components of the deflection. Based on a theoretical analysis by Wyman (1950) on the deflection of a loaded infinite plate,
the test results are used to calculate the characteristic length ($l$) and the strain modulus ($E$) of the ice.

The results of the tests for both EG/AD/S ice and urea model ice are shown in Fig. 22. From this figure, it is evident that there is no apparent difference between the modulus for the two types of model ice when compared under comparable conditions. Thus, the EG/AD/S ice maintains the good $E/\sigma_F$ ratio of the urea ice. For this ice, the range of $E/\sigma_F$ ratios is $1,500-2,500$ over the whole range of flexural strengths (i.e. scale factors). This ratio is at the lower end of the corresponding $E/\sigma_F$ ratios in nature of $2,000-8,000$ and is, overall, less than the average value for both cold and warm sea ice. Thus, although the $E/\sigma_F$ ratio for EG/AD/S ice is the same as that for urea ice, the modulus is scaled only to the lower limit of the value that it should be.

5.5 Fracture toughness

The fracture toughness is a material property which defines the stress necessary to propagate a crack of a known size. It is usually expressed in terms of the critical stress intensity factor, $K_{ic}$ (see e.g. Ewalds and Wanhill, 1984). There have been a number of investigations of the fracture toughness of freshwater ice including Gold (1963), Goodman (1980) and Urabe and Yoshitake (1981a). Measured values of $K_{ic}$ range from 60 to 300 kPa m$^{1/2}$. The tests indicate that the fracture toughness decreases with increasing loading rate, increasing temperature and decreasing grain size. For sea ice, comparatively fewer studies have been done (Urabe and Yoshitake, 1981b; Timco and Frederking, 1983a). A compilation of all test results is shown in Fig. 23. Measured values of $K_{ic}$ range from 30 to 140 kPa m$^{1/2}$ with an apparent decrease in $K_{ic}$ with increasing brine volume. From this figure, representative values for cold and warm sea ice are chosen to be $120$ kPa m$^{1/2}$ and $80$ kPa m$^{1/2}$ respectively. These values will be used in this analysis for scaling purposes. To correctly simulate cracking activity in the model tests, these values should be reduced by $\lambda^{3/2}$ where $\lambda$ is the geometric scale factor for the tests (Atkins, 1975).

In measuring the fracture toughness for the model ice, the 3-point loading configuration was used. In this technique, a beam of length $L$, width $W$, and thickness $H$ is loaded at three equidistant loading points such that the centre loading point is parallel to but opposed to the two end loading points. A notch or “crack” of length “a” is cut into the ice on the face opposite the central applied load and sharpened using a surgeon’s scalpel. The critical stress intensity factor is given by

$$K_{ic} = \frac{3PLa^{1/2}}{2WH^{2}} f(a/H)$$

where

$$f(a/H) = 1.93 - 3.07 \left(\frac{a}{H}\right) + 14.53 \left(\frac{a}{H}\right)^2 - 24.11 \left(\frac{a}{H}\right)^3 + 25.80 \left(\frac{a}{H}\right)^4$$

(Brown and Srawley, 1966). This equation is valid for a $L/H$ ratio of 4 and $a/H$ ratio up to 0.6. In order for the test to be valid, however, both the crack length ($a$) and width ($W$) must be greater than 2.5 ($K_{ic}/\sigma_F$)$^2$ where $\sigma_F$ is the tensile yield strength (Brown and Srawley, 1966). For this ice, however, neither $K_{ic}$ nor $\sigma_F$ is known. Therefore, to get an estimate of the minimum value for $a$ and $W$, a relatively high $K_{ic}$ value of 6 kPa m$^{1/2}$ at $\sigma_F = 40$ kPa was chosen, and, assuming $\sigma_F = \sigma_y$ and using the above condition, a minimum length of 5.6 cm is obtained. Thus, this necessitates the use of relatively large samples. For model ice, however, this can present a problem due to the mechanically weak nature of the ice. Since $a > 5.6$ cm and it is desirable to have the crack length to sample thickness ($a/H$) less than 0.5, a beam thickness ($H$) of 14 cm was
chosen so that \( \frac{a}{H} = 0.4 \). The length of the beam should be smaller than the characteristic length, so a beam of length 50 cm was chosen. Thus \( \frac{L}{H} = 3.6 \). In performing the test, a beam 50 \( \times \) 14 cm was cut in the ice (of thickness 4 cm), and a notch of length 5.6 cm was cut in the centre of one of the 50 \( \times \) 4 cm faces. The notch was sharpened and the floating beam was loaded in situ in the 3-point loading arrangement. Thus, this loading arrangement measures the fracture toughness for vertically-oriented cracks propagating in the horizontal direction (i.e. similar to a radial or circumferential crack in a model test). In all cases, the loading times were on the order of 5 seconds, and the load-time curves were linear to failure. It should be noted that the width of the beam (or ice thickness in this case) should be greater than 5.6 cm in order to satisfy the requirement for plane-strain conditions. Since ice of this thickness is rarely used in model tests, it was decided that the results would be more meaningful if \( K_{IC} \) was measured for conditions in which model ice is used most often. The tests, therefore, were performed on ice of 4 cm thickness. These results give critical stress intensity factors which are in the transition range between plane-stress and plane-strain conditions (see e.g. Ewalds and Wanhill, 1984). As such, the values of \( K_{IC} \) will be slightly higher than the plane-strain \( K_{IC} \) values for model ice.

The results of the tests are shown in Fig. 24. Included on this figure are the results previously reported for urea ice (Timco, 1985) and the scaled

![Graph](image)

Fig. 24. Critical stress intensity factor versus flexural strength for both urea ice and EG/AD/S ice. Note the significant improvement in the scalability of the property for the EG/AD/S ice.

sea ice values. From this figure it is clear that the critical stress intensity factor for EG/AD/S ice is much lower than that for urea ice and it more correctly approaches the scaled sea ice values. This is a significant improvement. It means that EG/AD/S model ice will crack more readily than urea ice in such a way that it better simulates the cracking behaviour of ice. This has been observed by the author in several model tests using this new type of ice. In this regard, EG/AD/S ice is far superior to urea ice in correctly scaling the fracture toughness of ice.

### 6.0 SUMMARY

In the results, analysis and subsequent comparison with urea model ice and scaled prototype ice properties, there is no doubt that EG/AD/S ice is much superior to urea ice in virtually all respects. EG/AD/S ice maintains the ability to scale correctly the flexural strength over a wide range of scale factors while maintaining a good \( E/\sigma_F \) ratio similar to urea ice, and it has the added features of being single-layered, columnar in structure with better overall scaling of the flexural properties, uni-axial and confined compressive strengths, failure envelope and fracture toughness. In total, it appears to be a significant improvement in model ice technology.

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### REFERENCES


