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THE DEVELOPMENT OF A NEW TYPE OF MODEL ICE FOR REFRIGERATED TOW--ETC(U)

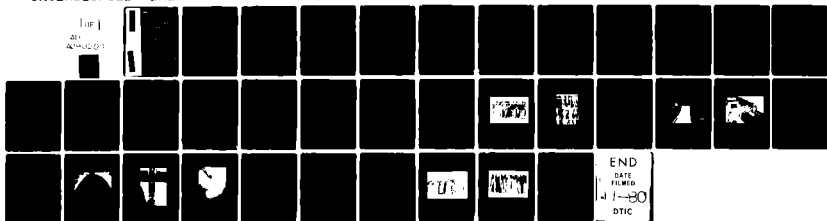
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THE DEVELOPMENT OF A NEW TYPE OF MODEL ICE FOR REFRIGERATED TOWING BASINS

by

G.W. Timco, J.F. Lane

Division of Mechanical Engineering

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MECHANICAL ENGINEERING REPORT

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**THE DEVELOPMENT OF A NEW TYPE OF MODEL
ICE FOR REFRIGERATED TOWING BASINS**

**(MISE AU POINT D'UN NOUVEAU TYPE DE GLACE DE SIMULATION
POUR BASSINS DE REMORQUAGE REFRIGERES)**

by/par

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ABSTRACT

A research program was initiated at the National Research Council of Canada to look for a new type of model ice which would accurately represent sea ice in its mechanical properties over a wide range of scaling factors. The results of this program are outlined in this report. The findings indicate that ice doped with either carbamide (urea) or lithium chloride would be a good model representation for sea ice for tests scaled up to 40:1.

RÉSUMÉ

Le Conseil national de recherches du Canada a lancé un programme de recherches dont l'objet était la mise au point d'un nouveau type de glace de simulation qui reproduirait avec précision les caractéristiques mécaniques de la glace de mer sur une vaste gamme d'échelles. Les résultats de ce programme sont exposés dans le présent rapport. En bref, ils indiquent qu'une bonne glace de simulation est obtenue en dopant de la glace ordinaire avec du carbamide (urée) ou du chlorure de lithium et qu'on peut l'utiliser avec succès pour des tests d'échelles allant jusqu'à 40:1.

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THE DEVELOPMENT OF A NEW TYPE OF MODEL ICE FOR REFRIGERATED TOWING BASINS

1.0 INTRODUCTION

The Canadian coastline is 16,000 km long and extends from 41° 41' north latitude to 83° 09' north latitude. Along this long coastline every imaginable icing condition exists from fresh water ice in the Great Lakes and St. Lawrence Seaway to the continuously frozen bays and fiords of the Canadian Archipelago in the high Arctic. The search for oil and other natural resources in the Arctic has made it necessary that Canada have a capability to maintain structures and transport goods along its entire coastline. In 1973 the Canadian Government announced an Oceans Policy and one element in that policy was the development of "an internationally recognized excellence in operating on or below ice-covered waters". An integral part of the policy was the development of facilities for the design and testing of ships, submarines and other vessels for ice-covered waters. The responsibility for developing these facilities was assigned jointly to Transport Canada and the National Research Council.

The construction of large structures such as drilling platforms and ice breakers entails a large expenditure of money and it is therefore normal that model studies be carried out to determine the most economical and efficient configuration. The National Research Council, because of its expertise in testing of ships in the Marine Dynamics and Ship Laboratory, was assigned the task of developing an ice tank for the testing of structures in ice-covered waters⁽¹⁾.

A review of modelling techniques in 1975 when the construction of an ice tank was first proposed, revealed that the model ice available at the time did not correctly reproduce real sea ice to scale. A number of techniques were available for correcting for the inaccuracies of the model ice in use, but when these techniques were compared with each other they yielded greatly different results.

At this time model ice was being prepared by freezing a saline solution and then warming the surface to weaken the ice. Using this ice, accurate scaling from 5:1 to 20:1 was attainable. However, for today's large freighters, scale factors up to 40:1 were required in order that the model ship was not excessively large. A new testing medium was required.

The task of developing the new medium was assigned to the Low Temperature Laboratory because of its expertise in dealing with environmental icing problems and its facilities for making ice. The problem was assaulted with a multi-part program as follows:

1. A review of the available data on the physical properties of sea ice to determine the actual conditions which were to be modelled.
2. A review of the scaling laws affecting the testing of structures in ice in order to define the properties of a suitable model ice.
3. A study of the structural properties of doped ice in an attempt to determine the factors controlling the strength of the ice.
4. A chemical survey to define those chemicals which could be used to dope the ice in a refrigerated towing basin.
5. Small scale tests to determine the effectiveness of these chemicals in reducing the strength of the ice.
6. Testing the mechanical properties of large ice sheets doped with the most effective strength reducing chemicals to determine which, if any, chemicals produced a suitable model ice.

This report outlines the results of these programs.

2.0 PHYSICAL PROPERTIES OF SEA ICE

When sea ice forms, the ice tries to reject the salt impurities and freeze in a pure state. For various reasons, however, this is not accomplished and the ice forms with some salt and brine inclusions trapped within it. During growth, this liquid brine is trapped and contained at inter-crystalline boundaries and in thread-like pockets or cells which, for depths below ≈ 30 cm, are all aligned in the vertical direction. In general, the size and shape of the brine inclusions are a complex function of the ice salinity and temperature. However, the amount of liquid brine (i.e. the brine volume ν_b) within the ice can be readily determined for any temperature and salinity from the relationships developed by Frankenstein and Garner⁽²⁾. For temperatures in the range -0.5°C to -22.9°C the brine volume is given by⁽²⁾

$$\nu_b = S \left(\frac{49.185}{\theta} + 0.532 \right) \quad (1)$$

where ν_b is the brine volume in parts per thousand (‰), S is the ice salinity in ‰, and θ is the absolute value of the ice temperature (in $^\circ\text{C}$). For first year sea ice, typical salinity profiles show average salinities of ≈ 5 ‰ which are derived from sea water of 35‰. For multi-year ice, brine drainage reduces the amount of salt present to typically 0.1‰ to 1‰.

Because of this system of solid salts and liquid brine inclusions in an ice matrix, a change in temperature alters the relative proportion of the solid and liquid phases in the ice. This in turn greatly affects the mechanical properties of the ice. To date, several experimental investigations have been carried out to measure the strength of sea ice, but because of the complex nature of sea ice and the differences in techniques for measuring sea ice strength, widely variable and conflicting results have been reported. Several review articles (Weeks and Assur^(3,4), Schwarz and Weeks⁽⁵⁾) have been published which give detailed overall views of these results, and the reader is referred to them for an appreciation of the complexity of the mechanical properties of sea ice. For the present purposes, however, it is of interest to note that for brine volumes less than 120‰, the strength (σ) of the ice can be related to the brine volume (ν_b) by a general equation of the form⁽³⁾

$$\sigma = \sigma_0 \left(1 - \sqrt{\frac{\nu_b}{\nu_0}} \right) \quad (2)$$

where σ_0 is the zero brine volume strength of the ice, and ν_0 is the brine volume required to give zero strength ice (see Fig. 1). Recently, Lane⁽⁶⁾ has reviewed the results of sea ice strength tests published in the open literature and compiled relationships of this type for the flexural, ring tensile, tensile, compressive and shear strength of sea ice and found that ν_0 is relatively independent of the type of ice strength tested ($\nu_0 \approx 200$ ‰). In the above form, the σ_0 values were found to be⁽⁶⁾

Flexural strength -- <i>in situ</i> cantilever beam test	850 kPa
Flexural strength -- simple beam test	2230 kPa
Ring tensile strength	2710 kPa
Brazil tensile strength	2890 kPa
Tensile strength -- tension test	810 kPa

Compressive strength — compression test index	1700 kPa
Shear strength -- single shear	1640 kPa
Shear strength — double shear	2710 kPa

It should be noted that these values are simply bulk averages from many strength tests and therefore they do not distinguish the effects of strain rate, sample size, shape or orientation, ice type, and size and orientation of the ice crystals. Nevertheless, this formulation gives some indication of the upper strength limits of sea ice.

For modelling purposes, the *in situ* cantilever beam test is normally used to determine the strength of sea ice. The results of a number of cantilever beam strength tests in the field are shown in Figure 1. The ice strength — brine volume relationship is:

$$\sigma = 850 \left(1 - \sqrt{\frac{\nu_b}{195}} \right) \text{ for } \sqrt{\nu_b} < 11.1 \quad (3)$$

$$\text{and } \sigma = 150 \text{ kPa} \quad \text{for } \sqrt{\nu_b} < 11.1$$

All *in situ* testing has been carried out where the top ice temperature is above -28°C and for ice less than 2 metres thick. Under these conditions the maximum strength of sea ice has been established as 500 kPa for design purposes. A requirement is developing for the operation of ice breakers, drilling ships and drilling platforms in the Arctic in much thicker ice and much colder temperatures. Using a technique suggested by Frankenstein⁽⁷⁾, Lane⁽⁸⁾ has estimated the strength of level sea ice for thicknesses up to 4 metres thick and with top ice temperatures down to -40°C . The resulting strength map is shown in Figure 2. It is evident from the strength map that average first-year level sea ice flexural strengths as high as 750 kPa may be encountered in the high Arctic in mid-winter.

Ice thickness in the Arctic varies from open leads to fully consolidated ice ridges with keel depths of 20 metres or more. Thorndike⁽⁹⁾ et al estimated that at the end of the winter season 48% of the Arctic ice would exceed 3.2 metres (10 ft., 6 in.) and 10% would exceed 6 metres (20 ft.) in thickness. Along the main coast lines, ice thicknesses of 2-3 m might be expected at winter's end.

3.0 THE SCALING LAWS FOR MODEL ICE

The ice used in model testing must meet certain scaling laws in order to guarantee similitude with the prototype system. The conditions required for similitude have been described by Nevel⁽¹⁰⁾, Vance⁽¹¹⁾, Michel⁽¹²⁾ and Schwarz⁽¹³⁾. In model testing, it is important that geometric (i.e. linear dimensions), kinematic (i.e. velocities) and dynamic (i.e. forces) similitude be preserved. This entails maintaining as faithfully as possible in the model (m) system the relative importance of each of the independent forces acting in the full scale, prototype (p) system. This criterion leads to

(1) the Froude number (F_n)

$$F_n = \frac{\text{inertial forces}}{\text{gravitational forces}} = \frac{v_p}{\sqrt{L_p g_p}} = \frac{v_m}{\sqrt{L_m g_m}} \quad (4)$$

where v = velocity, L = length, and g = gravitational acceleration;

(2) the Reynolds number (R_n)

$$R_n = \frac{\text{inertial forces}}{\text{viscous forces}} = \frac{v_p L_p}{\nu'_p} = \frac{v_m L_m}{\nu'_m} \quad (5)$$

where ν' = viscosity;

(3) the Cauchy number (C_n)

$$C_n = \frac{\text{inertial forces}}{\text{elastic forces}} = \frac{\rho_p v_p^2}{E_p} = \frac{\rho_m v_m^2}{E_m} \quad (6)$$

where ρ = density, E = strain modulus.

As a consequence of this, the physical properties of both the model structure and the model ice must meet certain well-defined requirements.

In particular, the model ice must scale according to

$$\sigma_p = \lambda \sigma_m \quad (\text{ultimate strength relationship})$$

$$E_p = \lambda E_m \quad (\text{elasticity relationship})$$

$$h_p = \lambda h_m \quad (\text{ice thickness relationship})$$

$$f_p = f_m \quad (\text{frictional relationship})$$

$$\rho_p = \rho_m \quad (\text{density relationship})$$

$$g_p = g_m \quad (\text{gravitational relationship})$$

$$\mu_p = \mu_m \quad (\text{Poisson ratio relationship})$$

where λ is the geometric scaling factor for the test ($\lambda \geq 1$).

Since the density and frictional relationships are the same for both the prototype and model ice, it is difficult to substitute a material other than ice for modelling purposes. Alternative materials with the proper density have been developed but these do not have the proper coefficient of friction for modelling the frictional forces existing between the ice and the structure and between the pieces of broken ice. The requirement that both the ultimate strength (σ) and the Young's modulus (E) of the model ice be reduced substantially from that of natural ice makes it impossible to use ice frozen from pure water.

Several authors (Enkvist⁽¹⁴⁾, Vance⁽¹¹⁾, Schwarz^(13,15)) have stressed the importance of maintaining as faithfully as possible the E/σ ratio of the model ice. Since both E and σ scale by the scale factor λ , it follows that the E/σ ratio should be the same for both natural and model ice. Schwarz⁽¹⁵⁾ has carefully evaluated the E/σ ratio and determined that it is between 2000 and 5000 for sea ice. Thus, as a minimum requirement for model ice

$$(E/\sigma)_m > 2000 \quad (7)$$

This value must be achieved in model testing before the proper elastic characteristics of the ice can be obtained.

Based on the above discussion, the requirements for a model ice which will accurately represent level sea ice on a reduced scale can be ascertained. Scaling of the flexural strength (σ) requires that the model ice be extremely weak. For realistic scale factors (λ) of 30-40, this requires an ice strength of 20-25 kPa (based on a full scale value of 750 kPa). Moreover, since the E/σ ratio must be maintained, the model ice must have a strain modulus (E) value of at least 40-50 MPa in this strength range. Scaling of the ice thickness by λ is straightforward since this can be achieved by simply varying the freezing time. For scale factors of 30-40, the model ice thickness should be 5-6 cm to represent 2 m thick sea ice. Maintenance of the density, frictional coefficients and Poisson's ratio should be reasonably well accomplished for ice doped with most types of soluble impurities.

4.0 STRUCTURAL PROPERTIES OF ICE FROZEN FROM AN IMPURE MELT

In order to understand the process of producing strength-reduced ice, it is necessary to review briefly the structural factors controlling the strength of the ice. From both the macroscopic and microscopic viewpoint, there is little doubt that the crystal structure, crystalline size, packing arrangement of the ice grains, and both the size and shape of the impurity pockets in the ice will have a pronounced influence on the mechanical strength of a polycrystalline ice sheet. As such, the growth mechanisms, structural features of the ice and the methods for altering these features have to be understood as a first step in producing weak ice for model test basins.

When an ice sheet is grown from a doped water solution, the resulting ice structure has several distinct features which are characteristic of solidification from an impure melt. Figure 3 shows a polariscope photograph⁽¹⁶⁾ of a vertical thin section of ice grown from a self-nucleated 1% NaCl doped solution at an ambient air temperature of -20°C . The underlying grid is 1 cm on a side. It is evident from this photograph that the ice is composed of three distinct layers: (A) an upper layer which consists of small blocky grains. This layer is mechanically very hard since it is usually low in solute particles; (B) a thin transition layer which separates the upper region from the lower columnar zone. This layer is very distinct and usually has the highest impurity concentration⁽¹⁷⁾; and (C) a lower columnar layer which consists of long dendritic platelets, some of which extend from the transition layer to the bottom of the ice sheet. This layer is mechanically very weak.

The strength of ice grown from an impure melt can be directly correlated to the thickness of the upper layer (Timco⁽¹⁸⁾). Since the thickness of this layer decreases with increasing initial impurity content in the melt, weak ice will only be produced when grown from solutions with sufficient impurity concentration to produce dendritic growth. Moreover, because the lower dendritic region (C, Figure 3) has very little strength, the weakest ice would result when using a dopant which brings about the dendritic growth quickly (i.e. that makes A as small as possible).

A petrographic study⁽¹⁹⁾ of the fracturing process in doped ice has shown that the fracture plane is controlled by the substructure of the ice. For fracture in the vertical plane, the break is intercrystalline (i.e. along grain boundaries) in the upper layer (A, Fig. 3), but may be either inter- or transcrystalline (i.e. across grain boundaries) in the lower region (C, Fig. 3). For maximum strength reduction, it is desirable to have a large number of small grains in the upper layer, preferably with a vertical columnar structure, since this would increase the probability of fracture in this region. This can be achieved by nucleating the cold water with a fine mist fog (wet-seeding) as shown in Figure 4.

Finally, the strength of the ice will also be influenced by the size, shape, alignment and spacing of the impurity pockets in the ice. Since the liquid impurity volume increases with increasing temperature, for strength reduced ice it is necessary to warm the ice sheet after the freeze (Schwarz^(13,15)). Using the standard Griffith crack theory⁽²⁰⁾ of an elastic instability in a brittle material, Timco⁽¹⁹⁾ estimated that the length of impurity pocket necessary to produce 20 kPa ice is on the order of 5 cm, i.e. the thickness of the ice sheet. Since brine cell lengths in relatively warm sea ice are on the order of 1.5-3 cm^(21,22) it would seem that a *warming technique*^(13,15) would be a necessary step in producing weak ice.

In summary, a review of the morphological properties of doped ice has indicated that to produce weak ice it is necessary (1) to use a dopant of sufficient concentration to produce dendritic growth as soon as possible, (2) to nucleate the ice sheet in some way to produce small columnar crystals in the upper region, and (3) to warm the ice sheet after the freeze (see Timco^(18,19) for more detail).

5.0 A CHEMICAL SURVEY TO DETERMINE POTENTIAL DOPANTS

Having established the factors controlling the strength of the ice, it is now necessary to do a general chemical survey to determine which chemicals are suitable for use as a dopant in a model test basin. Before a chemical dopant can be tested for its strength-reducing effectiveness, it must meet the following set of criteria:

- (1) The dopant material must be soluble in (cold) water.
- (2) The dopant should readily mix with water to form a homogeneous solution.
- (3) The dopant should be non-volatile or with a low vapour pressure so that it does not evaporate before the ice sheet forms to trap it.
- (4) The melt solution should be non-corrosive and within a pH range of 4-10.
- (5) The dopant should be non-toxic and non-irritating to the skin, eyes and mucous membranes.
- (6) The dopant should be either biodegradable, non-polluting or be readily separable from solution (for disposal purposes).
- (7) The dopant should be relatively economical to use.

In setting up a systematic search for chemicals which do meet the above criteria and therefore are suitable for further testing, it is advantageous to review the Periodic Table and both inorganic and organic chemistry.

A general knowledge of the elements in the Periodic Table, including their scarcities, costs and hazards, leads to the exclusion of several groups including (1) transuranium elements, (2) noble gases, (3) rare earth metals, (4) Actinide series, (5) elements in Periods 4, 5 and 6 except potassium, calcium, copper, manganese and nickel, and (6) miscellaneous elements in Periods 1, 2 and 3 including beryllium, boron, fluorine and sulphur. The remaining chemical elements can be considered under the headings of inorganic salts and organic compounds.

The series of inorganic salts provide a large number of candidates which potentially meet the desired criteria. There are two aspects which can be considered: (1) the series of constant cation salts (e.g. sodium salts) formed from different acids, such as hydrochloric (HCl), sulphuric (H₂SO₄) and carbonic (H₂CO₃), resulting in sodium chloride (NaCl), sodium sulfate (Na₂SO₄) and sodium carbonate (Na₂CO₃); and (2) the homologous series of salts obtained by replacing the hydrogen ion of one particular acid (e.g. HCl) by various electropositive metal ions (e.g. Li, Na, K, Ca, etc.), thereby forming the series LiCl, NaCl, KCl, CaCl₂, etc.). This can be done for a number of different acids. Clearly, the latter is simply an extension of the former, so that only the generalized salt of the different acids need be considered in terms of the required criteria.

Application of the above-discussed criteria leads to the exclusion of several of the inorganic salts. For example, on the basis of toxicity or corrosiveness, a large number of the inorganic salts must be excluded including the arsenates (-AsO₄), bromides (-Br), chromates (-CrO₄), fluorides (-F) iodides (-I), chlorates (-ClO₃), hydroxides (-OH), nitrates (-NO₃) and phosphates (-PO₄). In this category of inorganic salts, only the homologous series of chlorides (-Cl) and sulfates (-SO₄) meet all of the criteria for further testing⁽²³⁾.

In a survey of organic compounds, it is convenient to consider a simplified flow chart of organic chemistry (Fig. 5) in which the hydrocarbons are presented in row 1, with the addition of oxygen and its variations in row 2, and nitrogen and its variations in row 3. The symbol $R\cdot$ denotes the alkyl radicals ($R \equiv C_n H_{2n+1}$) and, as such, any general formula $R\cdot$ denotes a homologous series of chemicals. This chart was prepared following the discussion of Read⁽²⁴⁾. It is useful to follow this chart for the present purposes, since those organic chemicals which have similar characteristics are grouped together in a series. Thus, by evaluating the chemical series as a whole, those which do not meet the criteria can be eliminated from further consideration.

The hydrocarbons as shown in row 1 of Figure 5 can be broken into the *paraffin* series ($C_n H_{2n+2}$), the *olefine* series ($C_n H_{2n}$), the *acetylene* series ($C_n H_{2n-2}$), the *benzene* series ($C_n H_{2n-6}$) and *natural petroleum*. These must all be excluded since they are all generally water-insoluble and many are toxic and flammable.

The addition of oxygen as shown in row 2 of Figure 5 brings about the desired water solubility and presents a number of potential candidates including the $R\cdot OH$ alcohols, $H(CHOH)_n H$ alcohols, salts of fatty acids ($R\cdot COONa$), sugar carbohydrates, surfactant esters and emulsions. The other chemical groups in this row must be excluded on the basis of corrosiveness or toxicity (ketones, ethers, aldehydes, fatty acids) or non-solubility (carbohydrate non-sugars).

The addition of nitrogen in the third row brings about further possibilities. From this row the amides ($R\cdot CO\cdot NH_2$) and simple amino acids ($R\cdot CH(NH_2)\cdot COOH$) are suitable for testing, whereas the amines must be ruled out because of their toxic nature, and the proteins must be excluded because of their general high cost and high molecular weight.

In summary, this chemical survey has indicated that there are several chemicals which prove suitable for testing as potential dopants for model test basins. These include the homologous series of chlorides and sulfates, the alcohols, salts of carboxylic acids, surfactants, emulsions, sugars, amides and simple amino-acids (see Timco^(18,23) for more detail).

6.0 STRENGTH INDEX FOR DOPED ICE

Having established a definite set of chemical dopants which meet the criteria discussed in Section 5, it is of interest to test each of them (1) to determine their relative effectiveness in reducing the strength of ice, (2) to find the optimum concentration for each individual dopant, and (3) to determine general trends in the strength-reducing properties both within and between homologous series.

These experiments were performed by measuring the flexural strength of ice grown from doped solutions in 225-litre insulated plastic trays (see Fig. 6) which were refrigerated in a walk-in cold chamber. Heated vents were used to relieve the pressure built up by expansion due to the water-ice transformation. Two different approaches were taken to measure the flexural strength of the ice. Initially, the flexural strength was measured using the simple beam approach whereby a beam is constrained at its one-third points, and an opposing load is applied in the centre to rupture the beam (see Fig. 7). Using this technique, several chemicals were tested, and in particular, methanol-doped ice was studied in detail (see Shulhan et al⁽²⁵⁾, Timco et al⁽²⁶⁾). However, due to the difficulty in handling weak beams, and to gain consistency with the established modelling basins, the testing procedure was changed to measure the flexural strength of *in situ* cantilever beams. For these tests, the general procedure was to pre-cool the solution overnight at an ambient air temperature of $+2^\circ C$, and then freeze to form self-nucleated ice sheets at $T_f = -20^\circ C$ for ≈ 22 hours. After the freeze, the ice was allowed to warm up for 3 hours to an isothermal equilibrium of $\approx -0.5^\circ C$ before testing. Twelve cantilever beams were cut in the ice (length $L \approx 25$ cm, width $w \approx 6$ cm, thickness $h \approx 4$ cm) and standard push-pull gauges were used to determine the breaking load (P) of the ice. All cantilever tests were of the push-down type, and loading times were typically 1-2 sec. The flexural strength (σ) was calculated from

$$\sigma = \frac{6 P L}{w h^2} \quad (8)$$

and used as a strength index for the ice. For these small scale tests, no attempt was made to measure the strain modulus since, first of all, the tests were meant to present simply and quickly the amount of strength reduction for each chemical in ice, and, secondly, the ice was self-nucleated which would influence the strain modulus results.

In all, over 40 dopants were tested for solution concentrations up to 2%. Since the detailed results of these experiments are too voluminous to present here, only the general features of the results will be discussed. The full results of these tests have been published elsewhere (see Timco and Martin⁽²⁷⁾).

Figure 8 shows the flexural strength (σ) versus solution concentration (C_s) for ice doped with three different members of the homologous series of monovalent cation chlorides. Each point on the graph represents an average of at least 5 cantilever beam test results. From this graph it is evident that less of the lower molecular weight solute (i.e. LiCl) is required to bring about the desired strength reduction of the ice, and the saturation strength is higher for the higher molecular weight solute. Clearly, the most effective strength reduction occurs for the lowest member of the series. This general result was also found for the homologous series of divalent cation chlorides and both the monovalent and divalent cation acetates and sulfates.

In comparing the results among series, the strength reduction is not simply related to the average molecular weight of the dopant particles. Figure 9 shows the flexural strength (σ) versus solution concentration (C_s) for the sodium salts of the chloride (f.wt. = 58.5), the acetate (f.wt. = 82) and the sulfate (f.wt. = 142) series. From this figure it is evident that the effectiveness of the strength-reducing properties on ice for these dopants varies for each series, and is not simply related to the average, post-electrolytic molecular weight of the dopant. In fact, there was a wide variance in the strength-reducing properties of the various chemicals tested. In general, the chlorides (except LiCl) were, for a given weight and considering their electrolytic nature in solutions, of only average effectiveness for producing strength-reduced ice. The sulfates were reasonably effective, especially considering the relatively high molecular weight and high eutectic temperature of the series. The alcohols of general form $R \cdot OH$ were extremely effective in producing weak ice. However, ice grown from $R \cdot OH$ alcohol doped solutions with concentrations greater than 0.3% were quite porous with a distinct skeleton layer. The alcohols of general form $H(CHOH)_n H$ were, except for methyl alcohol, only moderately effective in reducing the strength of the ice. The salts of the carboxylic acids, especially the acetate series, were very effective in producing strength-reduced ice. The surfactants, when added to a NaCl doped melt, resulted in very weak ice which had a very fine crystalline structure. Oil-water emulsions also produced weak ice, but the frictional characteristics of this ice would make it unsuitable for use in a model test basin. Carbohydrate sugars and the simple amino-acids were ineffective, whereas the amides were very effective in producing strength-reduced ice.

In summary, this testing has shown that (1) within a homologous series, the greatest strength reduction generally occurs for the lowest member of the series, and (2) of the dopants selected for study from the chemical survey, the most effective ice strength-reducing ones were the $R \cdot OH$ alcohols, the acetates and the amides.

7.0 PHYSICAL PROPERTIES OF LARGE ICE SHEETS GROWN WITH SELECTED DOPANTS

Having established the chemicals and chemical families which effectively reduce the strength of ice, it is necessary to determine the flexural strength (σ) and strain modulus (E) properties of large ice sheets doped with these selected dopants. At least one chemical from each of the three chemical groups as well as several miscellaneous chemicals were tested. For these tests, a pool 6 m long by 3 m wide by 1 m deep was constructed inside one of the large walk-in cold chambers in the Low Temperature Laboratory (see Fig. 10). The pool walls were made of braced aluminum sheets with 7 cm of styrofoam insulation along the outside. An inner vinyl liner provided a water-tight seal, and a cat-walk was built around all sides of the pool at its top height. A four-wheel carriage extending across the pool running on angle iron tracks was constructed to allow access to any part of the pool.

In growing an ice sheet, the ice was nucleated using a wet-seeding technique. The general procedure for producing an ice sheet was to pre-cool thoroughly the solution at an ambient air temperature of +2°C, and then lower the air temperature to -20°C. When an ice skim had started to form over a part of the pool, the refrigeration equipment was shut off, and the ice on the water's surface was quickly cleared using a full-width screen which was pulled along the length of the pool. The solution was then wet-seeded using two water bottles attached to air lines and equipped with #180 (air) - #40100 (water) spray nozzles. This produced a fine misty-like fog in the room which settled on the water's surface and nucleated the ice sheet to produce a fine crystalline pattern. When an ice skim had formed covering the whole surface, wind deflectors were placed above the surface to ensure that the initial ice formation grew under quiescent conditions, and the refrigeration equipment was restarted to freeze at -20°C. Typical freezing times of 16-18 hours produced ice of 4-5 cm thickness.

In testing an ice sheet the general procedure was, first of all, to determine the strain modulus. This was done by loading (P) the ice at the centre of the pool, and measuring the resulting deflection (δ) at a point immediately adjacent to the load (see Fig. 11). This enabled a calculation of the characteristic length (ℓ) for the ice sheet from⁽²⁸⁻³⁰⁾

$$\ell = \frac{.8P}{2\pi\rho g\delta}^{1/2} \quad (9)$$

where ρ is the density of water and g is the gravitational acceleration. The strain modulus (E) is then determined by

$$E = \frac{12\rho g(1-\mu^2)\ell^4}{h^3} \quad (10)$$

where h is the thickness of the ice cover and μ is Poisson's ratio. Immediately following this, a series of four to six cantilever beams ($L \approx 20$ cm, $w \approx 10$ cm, $h \approx 4$ cm) were cut along one edge of the pool to establish a strength index for the ice (see Fig. 12). This procedure was repeated several times throughout the day as the ice sheet warmed up. Thus, the physical properties were determined as a function of temperature (i.e. the liquid impurity volume in the ice). This enables a determination of a series of $E - \sigma$ points for each concentration of the dopants tested. The full results for each of the dopants tested are too voluminous to present here, and the reader is referred to Timco and Martin⁽³¹⁾ for full details. In this section, the general results are outlined.

The first series of tests were performed on ice grown from a 0.6% NaCl solution, primarily to verify the present test techniques in comparison with those used in other model test basins. This type of solution is that used by the HSVA ice test basin in Hamburg, Germany, and it was chosen because its behaviour has been well documented in the literature. According to Schwarz^(13,15) during the warm-up period after the freeze, the ice exhibits a broad maximum in its E/σ ratio on the order of 2000 for strengths about 50 kPa. This general behaviour is in agreement with that observed by the present experiments (Fig. 13). This is the optimum E/σ ratio for NaCl doped ice, and represents an accurate scaling factor (λ) on the order of 15-20.

Figure 14 shows the $E - \sigma$ results for ice grown from wet-seeded solutions doped with sodium acetate. In this figure there are several features to note. For each of the four concentrations tested, the effect of the warm-up on the ice is evident by following each of the curves from the top right-hand corner to the bottom left-hand corner of the figure. For ice grown from the low concentration solution (0.2%), the strain modulus was very large but decreased markedly with increasing warm-up time. In this case, however, the limiting flexural strength of the ice was ≈ 100 kPa which is far too

strong for use in model testing. With increasing impurity content in the melt, this $E-\sigma$ curve shifted towards lower limiting flexural strengths, with, however, an apparent clockwise rotation, such that for solution concentrations of 0.8%, the ice was quite weak (down to 10 kPa) but had a low E/σ ratio of 400 at this strength. This behaviour of a lateral shift to lower strengths accompanied by a clockwise rotation of the $E-\sigma$ curve with increasing solution concentration appears to be quite general and was observed for several of the doped ice tested.

In analyzing the results of these experiments, it was found that based on either the $E-\sigma$ properties or structure of the ice, several of the chemically doped types of ice were not suitable for use in refrigerated modelling basins. For example, ice containing either methyl alcohol or sodium acetate was unacceptable because it consisted of a definite two-layer system. Similarly, sodium sulfate doped ice was unacceptable because of its high strength and long warm-up period. Of the other chemicals tested, all produced $E-\sigma$ results which were superior to that produced by sodium chloride doping. In addition, structurally, they were suitable for use in modelling basins. The results for the optimum concentration for each of these chemicals is shown in Figure 15 along with the results for sodium chloride doped ice. Clearly, any of these types of ice would be better than sodium chloride doped ice in refrigerated modelling basins. It would seem, however, that there are two chemicals — carbamide (urea) and lithium chloride — which produce results which are superior to the others and meet the desired $E-\sigma$ requirements for a model ice over the full range of desirable scaling factors. Structurally, these types of ice are homogeneous (see Figs. 16 and 17) and appear to be well suited for use in refrigerated modelling basins.

8.0 DISCUSSION

In this study, the mechanical and structural properties of ice grown from chemically impure melts have been investigated in an attempt to find a doped ice which would have the desired properties for model ice in refrigerated modelling basins. Although there are several candidate chemicals which appear to be better than sodium chloride, there are two which are far superior to NaCl for producing model ice.

Ice doped with carbamide (urea) appears to offer a very good E/σ ratio of ≈ 2300 for strengths from 60 kPa down to 20 kPa with a reasonable warm-up time, crystal structure and overall mechanical properties (Timco⁽³²⁾). In addition, it is relatively economic (50 kgm \approx \$30 Can.), presents no toxic hazard⁽³³⁾, and since it is commonly used as fertilizer, it can be readily disposed of if required. A recent study by Minsk⁽³⁴⁾ on the corrosiveness of chemicals on concrete has shown that carbamide (urea) attacks concrete only slightly (rated 1 on a scale of 0 to 5 with 0 representing no corrosive action and 5 representing severe corrosive action), and therefore should be usable in a concrete environment with little difficulty. Determining the concentration of carbamide in solution is not as straightforward as that for sodium chloride, although techniques are available which can be used for determining the carbamide and ammonia ion concentration in solution (see e.g. Renfro and Patel⁽³⁵⁾). Finally, carbamide reportedly hydrolyzes in water forming a weak basic solution. This suggests that there might be a "fatigue" effect with this dopant, although tests by Timco⁽³²⁾ on a series of ice sheets doped with carbamide did not indicate any such effect*.

Ice doped with lithium chloride also offers an excellent E/σ ratio, especially for strengths in the range 40-60 kPa. In addition, this type of ice offers good overall mechanical properties (Timco⁽³⁶⁾). This dopant, however, is more than ten times more expensive than carbamide (50 kgm LiCl = \$440 Can.), although, of course, less lithium chloride is required in solution than carbamide. Lithium chloride is generally non-toxic (it is sometimes used to replace NaCl in salt-free diets⁽³³⁾) although it does have some hazard associated with it since it is a lithium compound. Determining its concentration in solution is straightforward since a conductivity cell can be used. In terms of its corrosiveness, it should fall somewhere between sodium chloride and carbamide.

* Since the initial release of this information at the P.O.A.C. 79 Conference in Norway⁽¹⁸⁾, several of the existing ice tanks including those in Canada, U.S.A. and Japan either have or are planning to convert their basins to a carbamide dopant (personal communication to G.W. Timco).

In summation, the choice of which of these two chemicals produces the best model ice is not clear-cut. The carbamide ice appears to offer the best overall properties since its E/σ ratio is good, it is non-toxic, non-corrosive, economical and readily disposed of if required. On the other hand, if the additional expense and longer warm-up time of the lithium chloride ice can be tolerated, it offers the best strain modulus-flexural strength properties of any of the types of ice tested. The choice of which chemical to use will have to be made by the individual ice tank operators depending upon their requirements. In any event, it is clear that model ice doped with either the carbamide or lithium chloride dopant is far superior to sodium chloride doped ice for use in refrigerated modelling basins.

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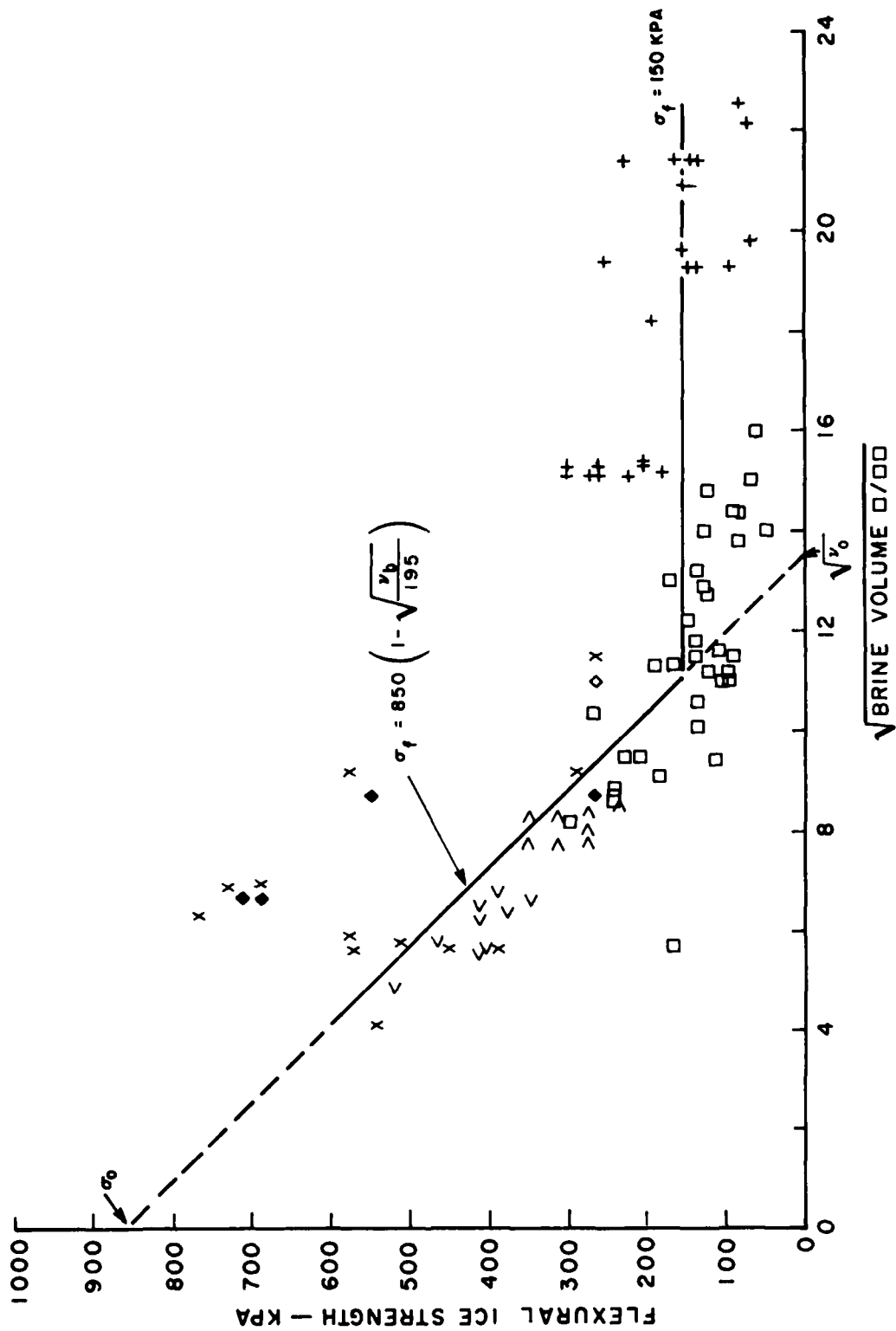


FIG. 1: SEA ICE STRENGTH - IN-SITU CANTILEVER BEAM TEST

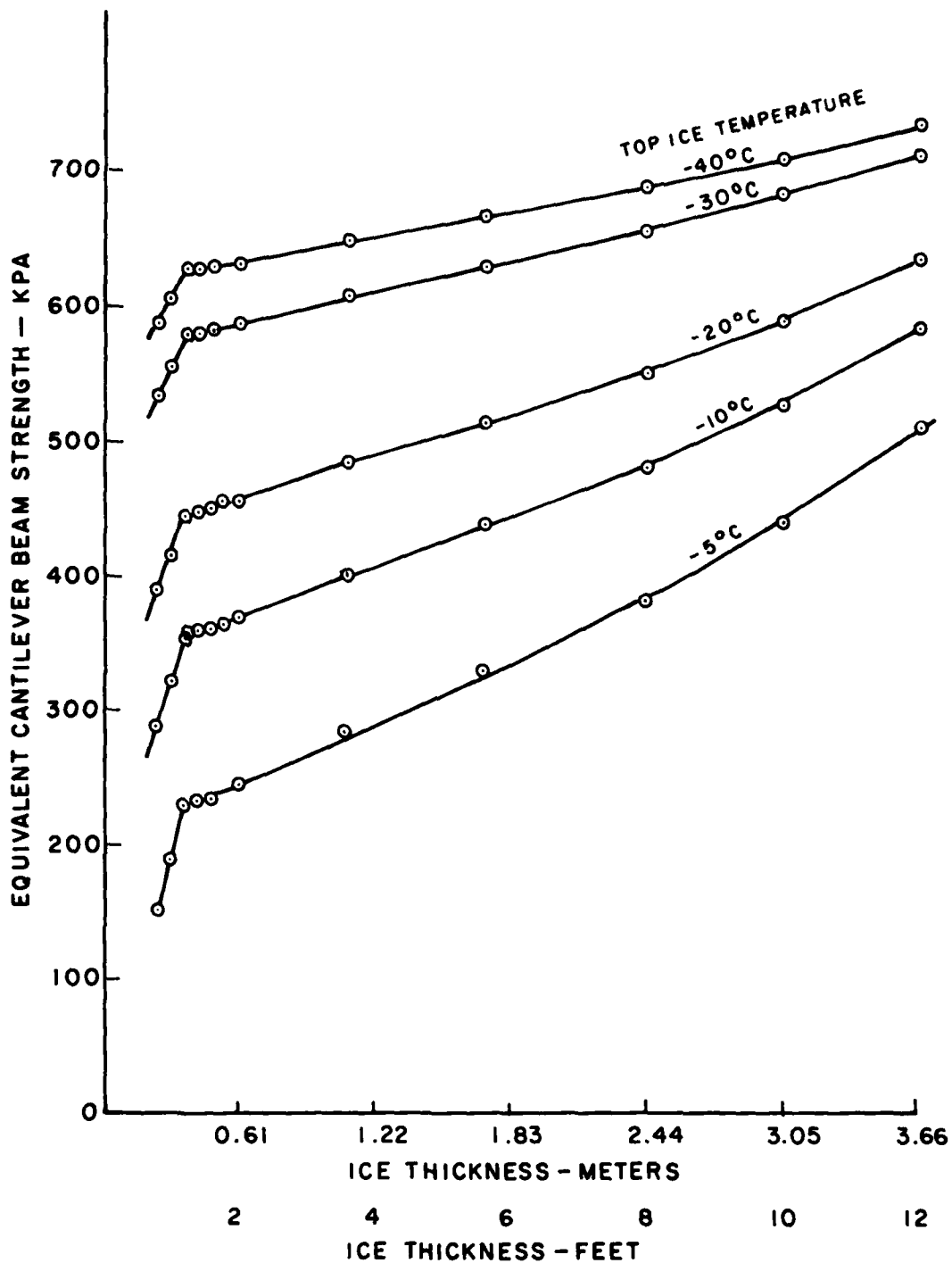


FIG. 2: ESTIMATED IN-SITU FLEXURAL STRENGTH OF SEA ICE FOR VARIOUS THICKNESSES AND TOP ICE TEMPERATURE



**FIG. 3: PHOTOMICROGRAPH OF A VERTICAL THIN SECTION OF 1% NaCl ICE TAKEN THROUGH CROSSED-POLARIDS. THE GRID IS 1 cm ON A SIDE.
NOTE: A - UPPER, MECHANICALLY HARD LAYER; B - THIN TRANSITION LAYER;
C - LOWER, COLUMNAR LAYER.**



**FIG. 4: PHOTOMICROGRAPH OF THE UPPER
PORTION OF A VERTICAL THIN SECTION OF
1% NaCl ICE GROWN WITH WET-SEED
NUCLEATION.**

**NOTE THE SMALL COLUMNAR GRAINS IN THE
UPPER LAYER. THE GRID IS 1 cm ON A SIDE.**

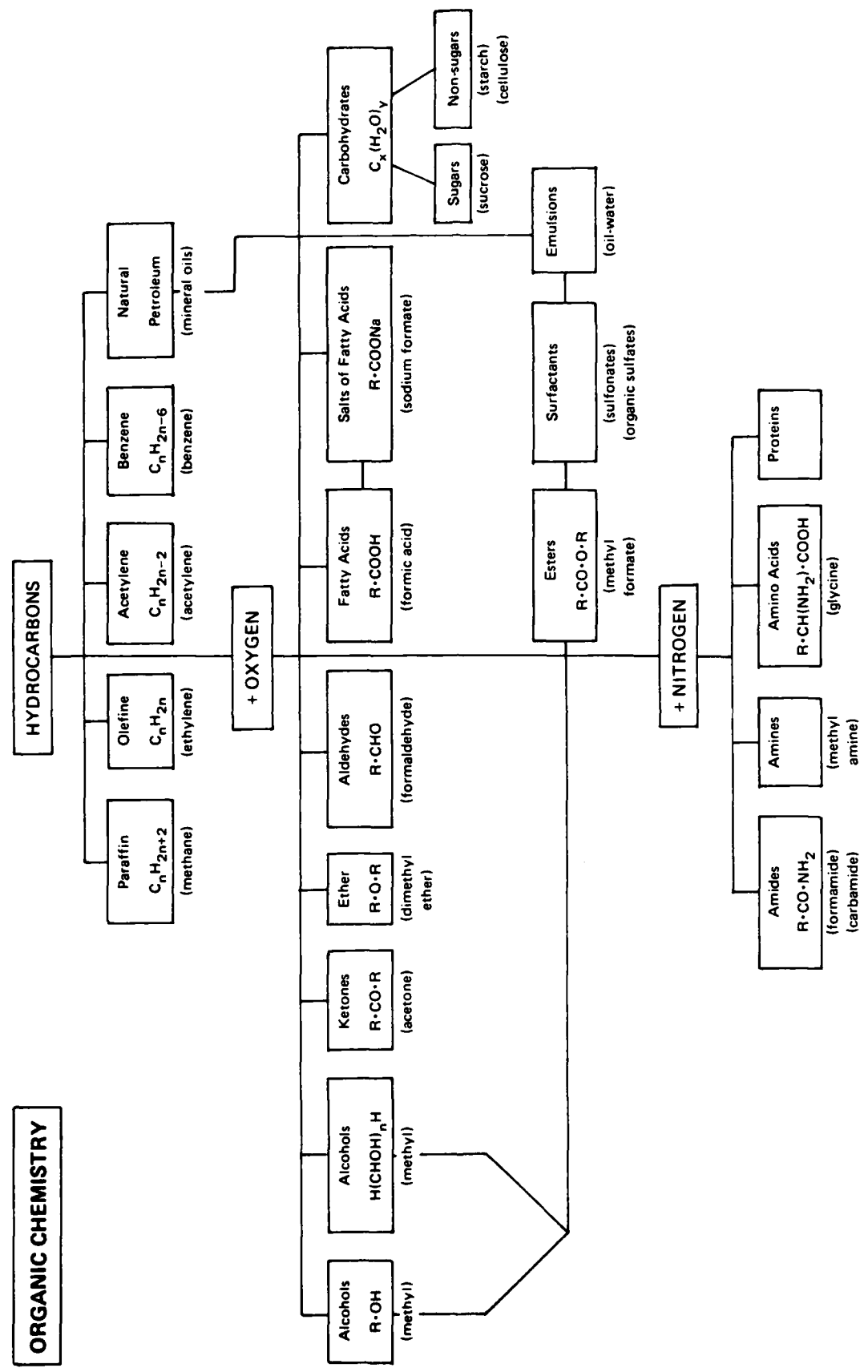


FIG. 5: SIMPLIFIED FLOW CHART OF ORGANIC CHEMISTRY. THE SYMBOL R DENOTES THE HOMOLOGOUS SERIES OF ALKYL RADICALS ($R \equiv C_n H_{2n+1}$).

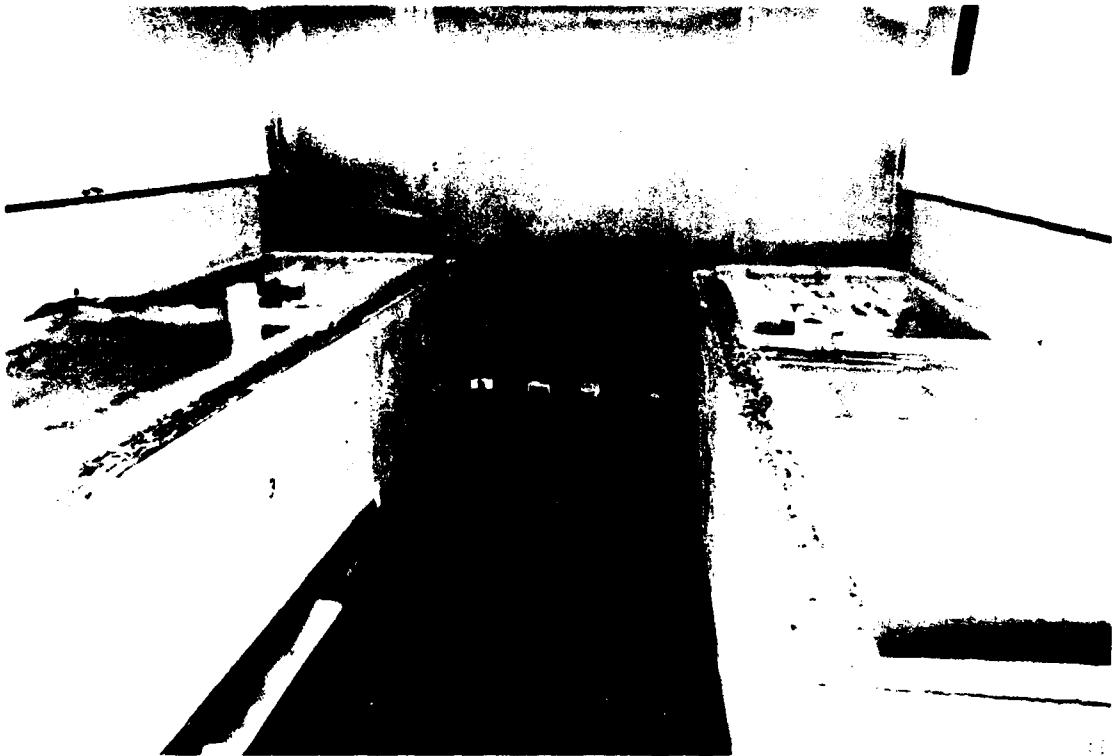
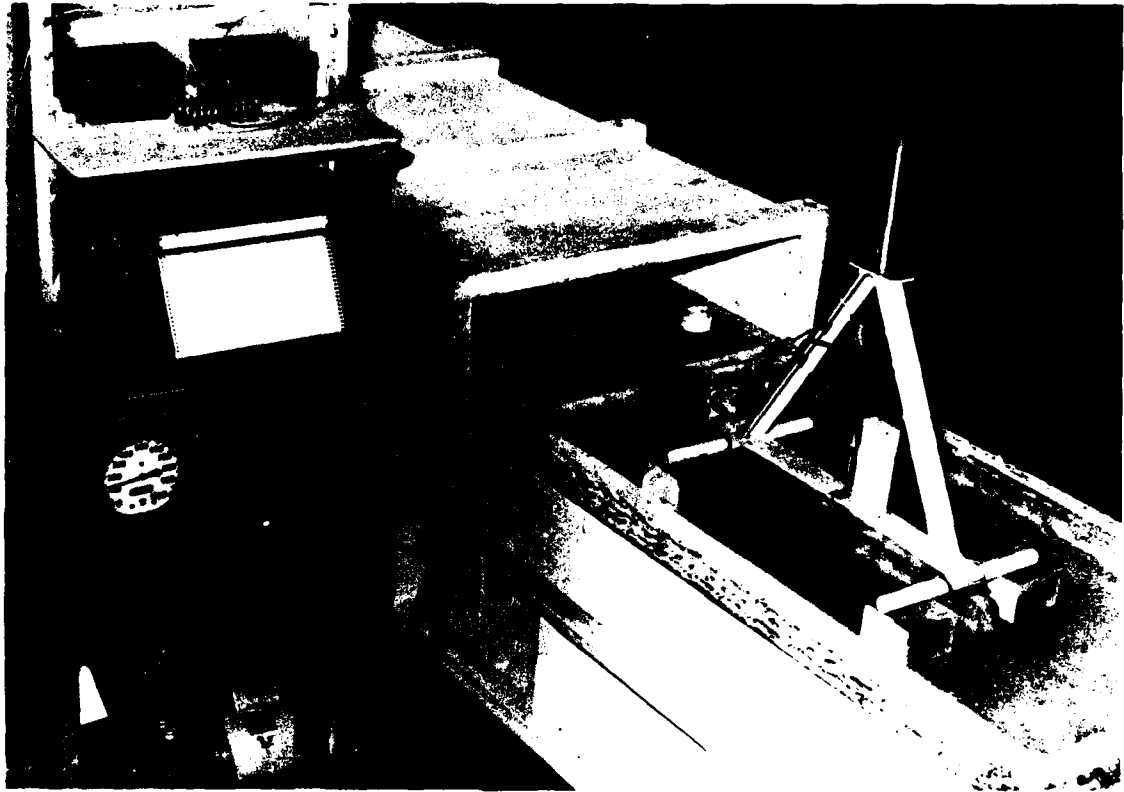


FIG. 6: PHOTOGRAPH SHOWING FOUR 225 LITRE INSULATED PLASTIC TRAYS WHICH WERE USED IN GROWING THE DOPED ICE FOR THE STRENGTH-INDEX TESTS.



**FIG. 7: PHOTOGRAPH SHOWING THE SIMPLE-BEAM APPARATUS INITIALLY
USED TO MEASURE THE FLEXURAL STRENGTH OF THE ICE.**

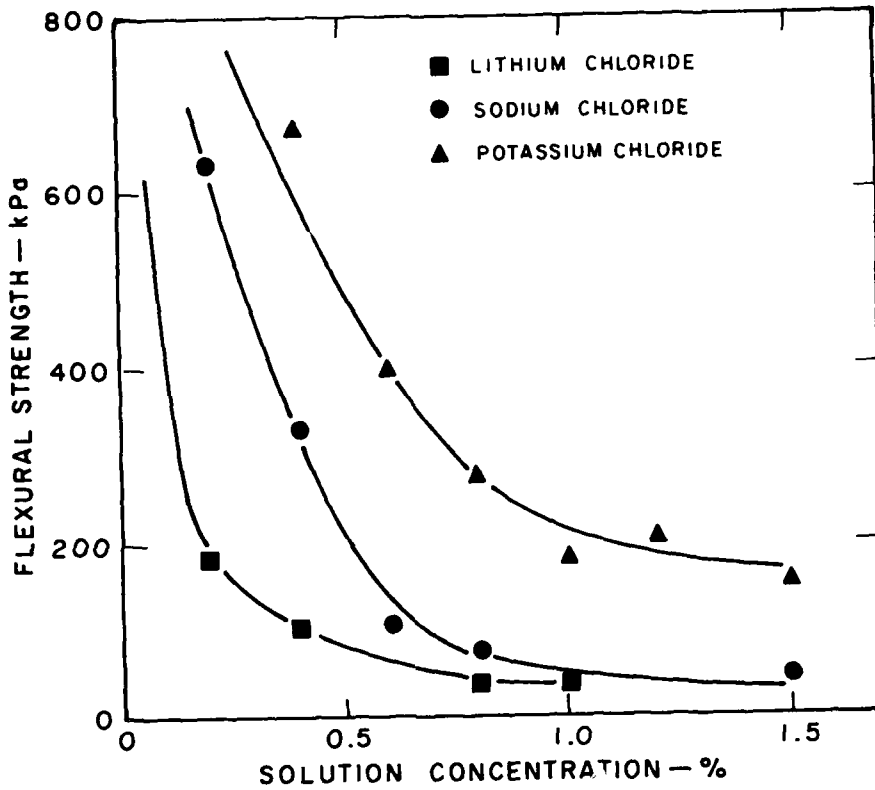


FIG. 8: GRAPH OF THE FLEXURAL STRENGTH VERSUS SOLUTION CONCENTRATION FOR SELF-SEEDED ICE GROWN FROM AQUEOUS SOLUTIONS CONTAINING THREE DIFFERENT MONOVALENT CATION CHLORIDES FOR A FIXED WARM-UP TIME OF 3 HOURS

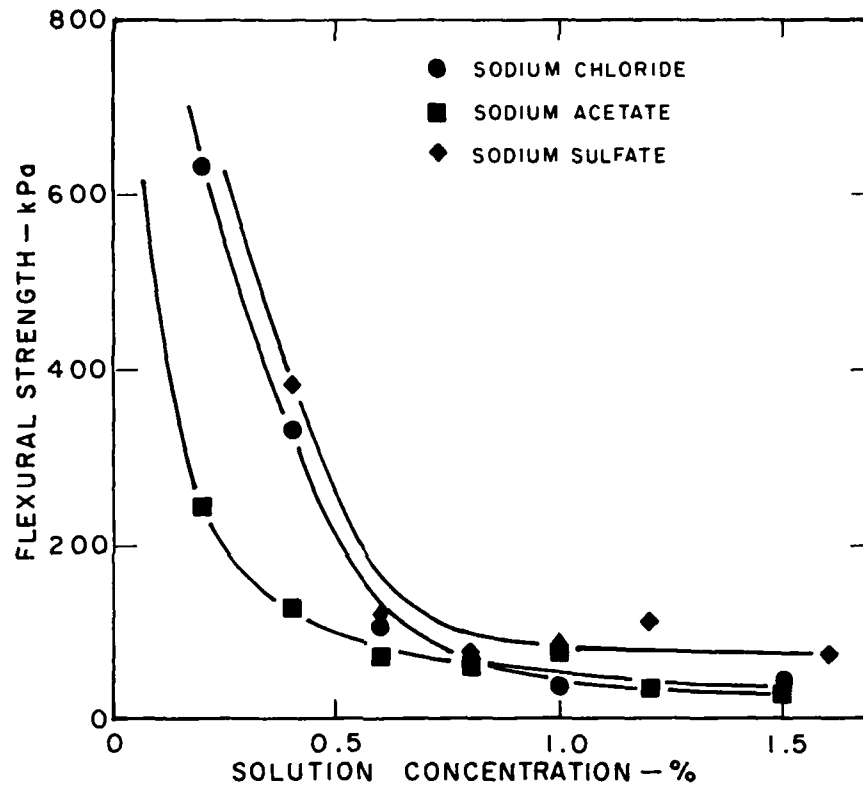
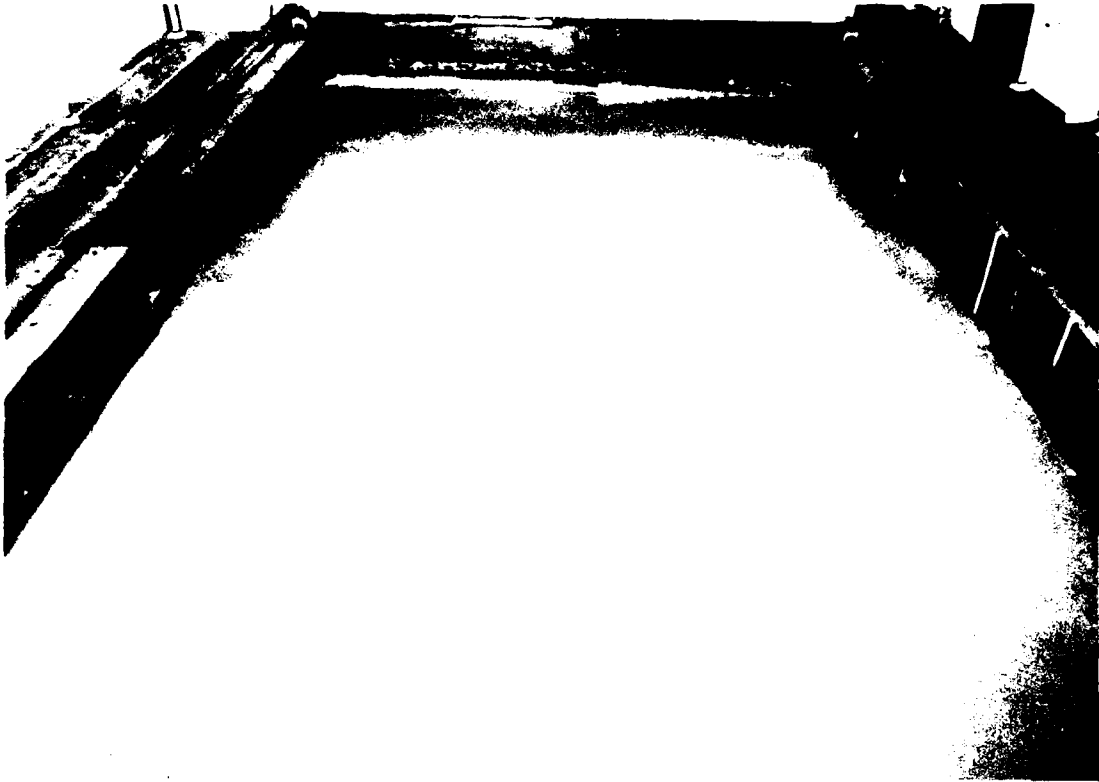


FIG. 9: GRAPH OF THE FLEXURAL STRENGTH VERSUS SOLUTION CONCENTRATION FOR SELF-SEEDED ICE GROWN FROM AQUEOUS SOLUTIONS CONTAINING SODIUM CHLORIDE, SODIUM ACETATE, AND SODIUM SULFATE FOR A FIXED WARM-UP TIME OF 3 HOURS



**FIG. 10: PHOTOGRAPH SHOWING THE POOL USED IN DETERMINING
THE MECHANICAL PROPERTIES OF LARGE ICE SHEETS**

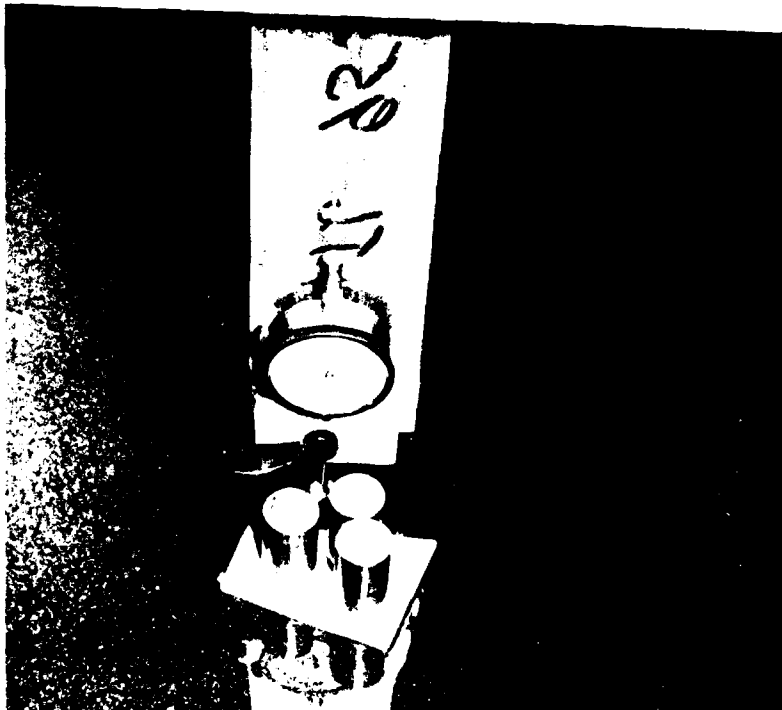


FIG. 11: PHOTOGRAPH SHOWING THE METHOD FOR DETERMINING THE LOAD-DEFLECTION CHARACTERISTICS OF THE MODEL ICE SHEETS



FIG. 12: PHOTOGRAPH SHOWING THE METHOD FOR MEASURING THE FLEXURAL STRENGTH OF THE ICE

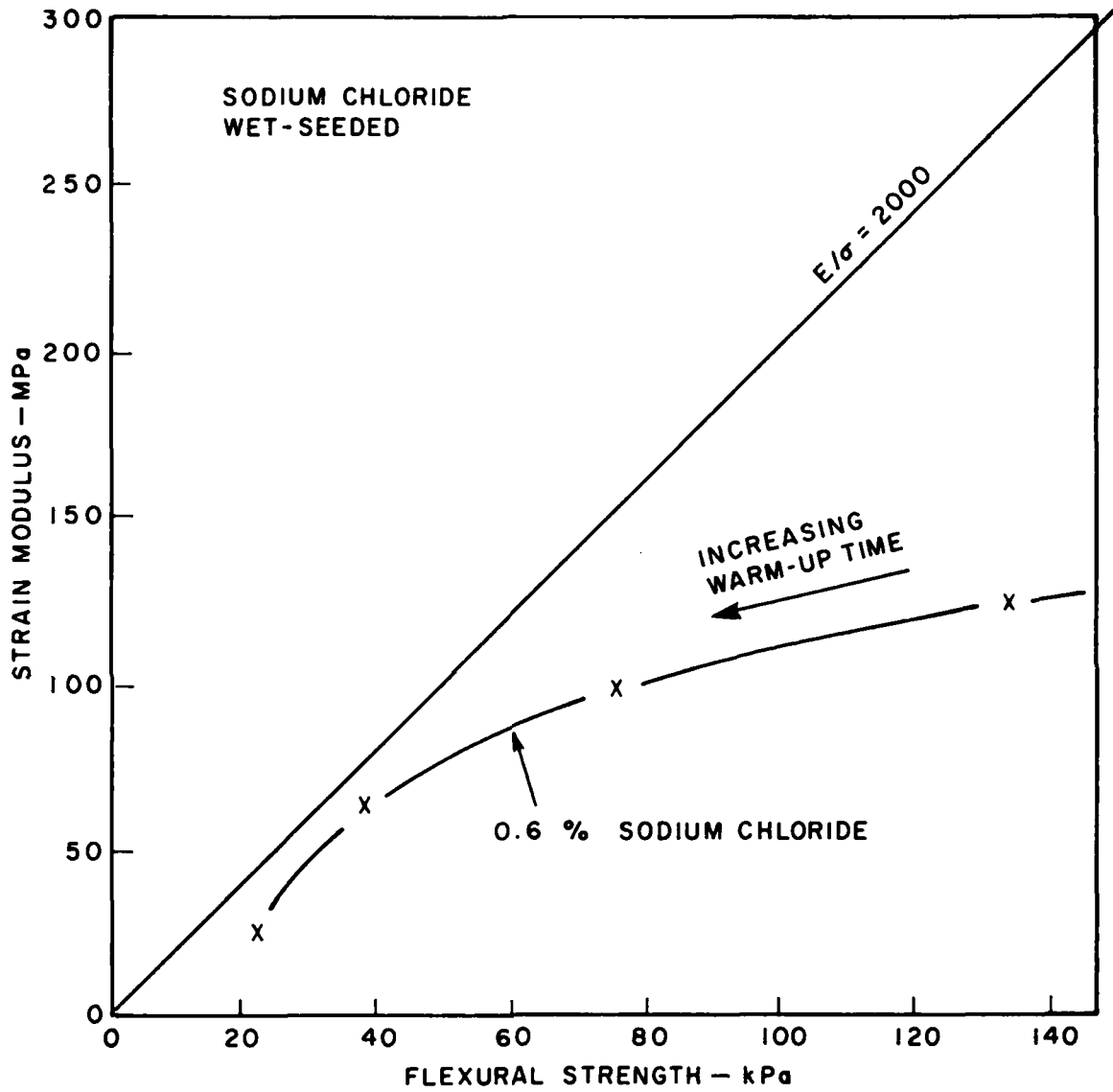


FIG. 13: GRAPH SHOWING THE OPTIMUM STRAIN MODULUS-FLEXURAL STRENGTH CHARACTERISTICS OF 0.6% SODIUM CHLORIDE DOPED ICE. FOLLOWING THE CURVE FROM RIGHT TO LEFT SHOWS THE EFFECT OF INCREASING WARM-UP TIME.

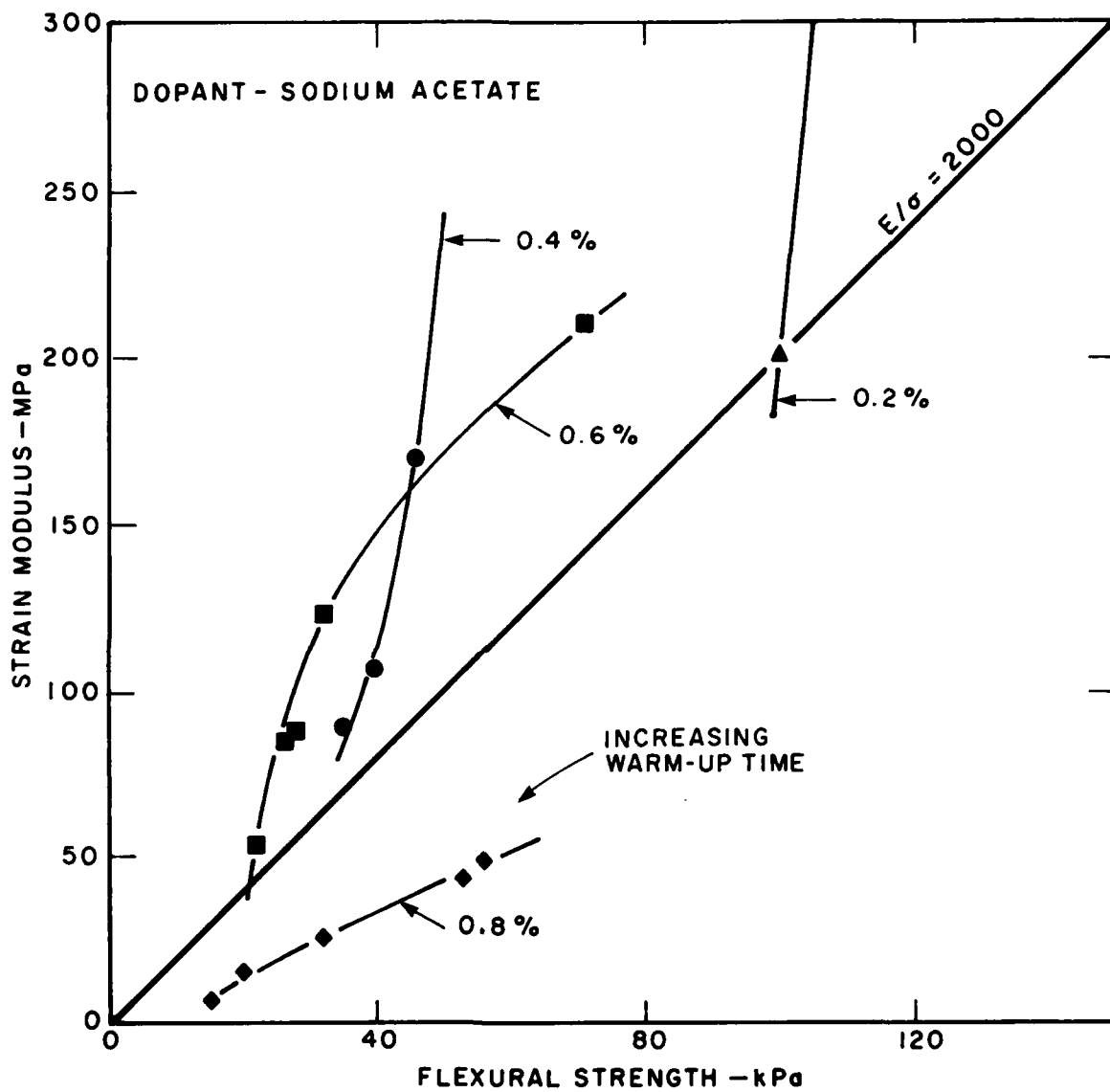


FIG. 14: GRAPH OF THE STRAIN MODULUS - FLEXURAL STRENGTH CHARACTERISTICS OF ICE GROWN FROM SOLUTIONS DOPED WITH VARIOUS AMOUNTS OF SODIUM ACETATE

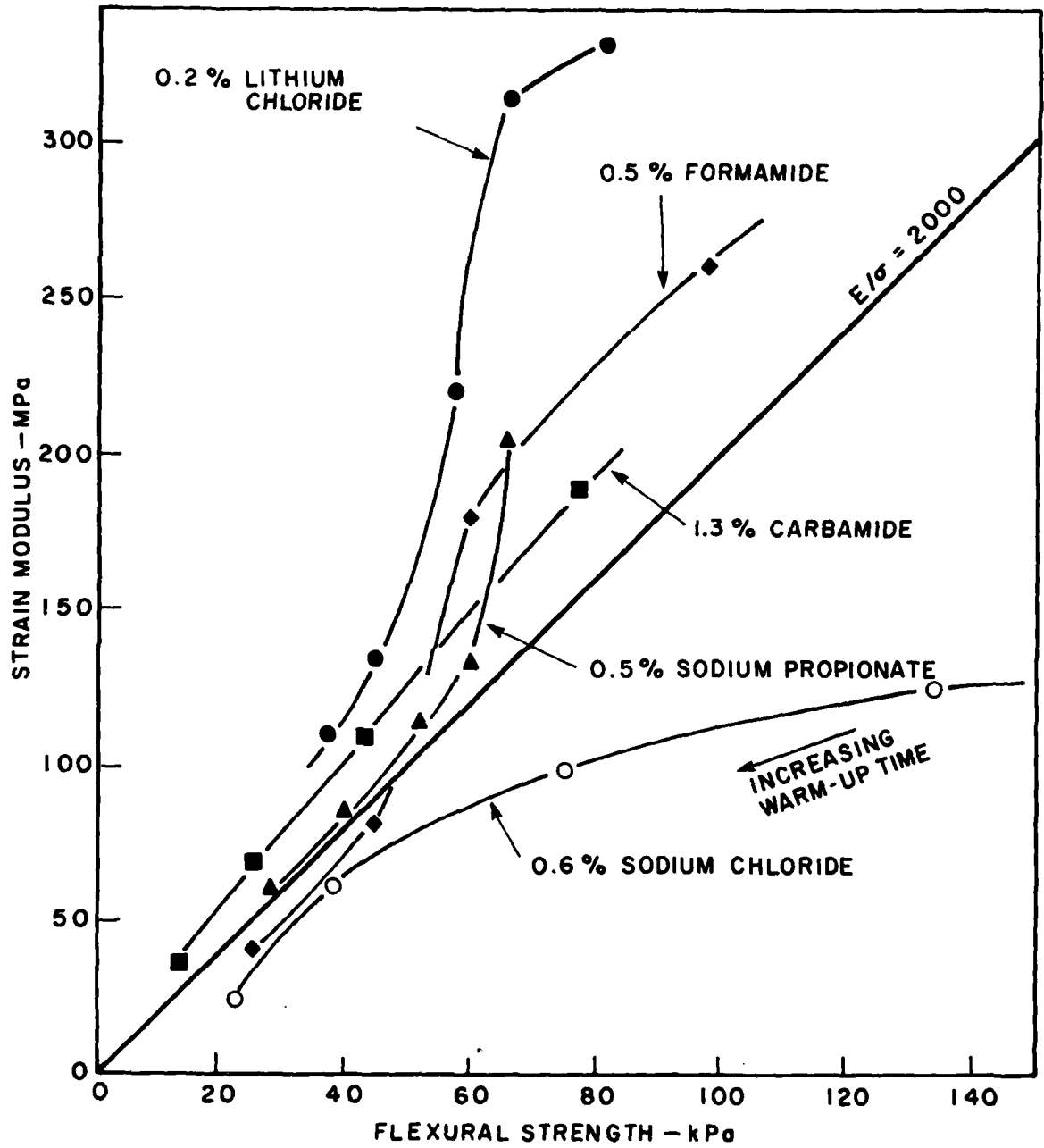


FIG. 15: GRAPH SHOWING THE OPTIMUM STRAIN MODULUS - FLEXURAL STRENGTH CHARACTERISTICS FOR FIVE OF THE DOPANTS TESTED



FIG. 16: PHOTOGRAPH SHOWING THE STRUCTURE OF WET-SEEDED ICE GROWN FROM A 1.3% CARBAMIDE SOLUTION. THE GRID IS 1 cm ON A SIDE.



FIG. 17: PHOTOGRAPH SHOWING THE STRUCTURE OF WET-SEEDS ICE GROWN FROM A 0.2% LITHIUM CHLORIDE SOLUTION. THE GRID IS 1 cm ON A SIDE.

