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SYG-ICE: A MODEL MATERIAL FOR RIVER ICE BREAKUP STUDIES

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ABSTRACT

In laboratory studies of river ice breakup, there is a need for a material which can simulate the behaviour of a natural ice cover. Such a material allows the study of the interaction between an ice jam and the retaining ice cover, and this interaction plays an important role in the formation and eventual removal of an ice jam. The material also permits the study of various methods of breaking of the cover such as by a surge or by an increase in the discharge in the channel. SYG-ICE is a newly developed synthetic material which is suitable for river ice breakup studies. It is made from a plaster mixture and its properties are close to the desired properties defined by the laws of similitude. Preliminary tests with large sheets of this material have produced encouraging results.

RÉSUMÉ

Afin de pouvoir étudier en laboratoire la rupture des embâcles de rivière, il est nécessaire de disposer d'un matériau de simulation du comportement de la couverture de glace naturelle. Ce matériau permettrait d'étudier l'interaction entre une embâcle et la couverture de glace qui la retient. Cette interaction joue en effet un rôle important dans la formation de l'embâcle et de son élimination éventuelle. Le matériau permet également d'étudier diverses méthodes de rupture du couvert de glace, par exemple, une poussée ou une augmentation de débit du chenal. Le SYG-ICE est un matériau synthétique récemment mis au point qui se prête aux études de rupture des embâcles de rivière. Ce matériau est fait d'un mélange de plâtre et ses propriétés se rapprochent des propriétés recherchées, définies par les lois de similitude. Des tests préliminaires réalisés sur de grandes feuilles de ce matériau ont produit des résultats encourageants.

MANAGEMENT PERSPECTIVE

Significant advances in river ice research can be made if ice breakup and jamming processes can be studied in the laboratory. Such work, however, is hindered by a general lack of suitable materials that can accurately model the natural ice cover under laboratory conditions.

This report describes an ice-substitute material called SYG-ICE which was developed at the National Water Research Institute. SYG-ICE has satisfactory physical and mechanical properties for studying the interactions between ice jams and intact ice covers. Moreover, SYG-ICE does not require refrigeration which is not only expensive, but could also produce thermal side-effects that are difficult to predict and control.

PERSPECTIVE GESTION

L'étude en laboratoire des processus d'embâcle et de rupture d'embâcle peut faire avancer de façon importante la recherche dans le domaine de la glace de rivière. Cependant, ces études sont généralement limitées par le manque de matériau permettant de reproduire exactement la couverture de glace naturelle en laboratoire.

Le présent rapport décrit un matériau imitant la glace, le SYG-ICE, mis au point à l'Institut national de recherche sur les eaux. Le SYG-ICE possède les propriétés physiques et mécaniques qui permettent d'étudier l'interaction entre les embâcles et les couvertures de glace intactes. De plus, il n'est pas nécessaire de réfrigérer ce matériau, ce qui est avantageux. En effet la réfrigération est non seulement coûteuse mais elle peut entraîner des effets thermiques secondaires difficiles à prévoir et à contrôler.

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1.0 INTRODUCTION

Significant progress in ice jam research can be made if the process can be studied in the laboratory where the flow and ice conditions can be controlled and where data can be easily acquired. To this end, an ice-substitute material is needed to accurately model the solid ice cover on a reduced scale.

Ice jams are complex phenomena, governed by a variety of natural processes that can be broadly classified as hydraulic, thermal and structural. To date, research has concentrated on hydraulic processes which are best amenable to laboratory and analytical study. Thermal aspects are also amenable to analysis though they are difficult to simulate in the laboratory. However, structural processes pertaining to ice jams remain largely unknown. At the same time, experience suggests that structural processes are very important in breakup initiation as well as the stability and release of ice jams that may form during the breakup period. The conditions for the release of an ice jam represent a question of great practical interest since it is closely related to peak breakup water levels and techniques to dislodge damaging jams.

More specifically, it is known that jams are usually initiated and held in place by intact sections of the winter ice cover. However, the interaction between the "driving" forces caused by the jam and the strength of the retaining ice cover is not understood at present. Field observations can only furnish "hints" of the pertinent mechanisms because important events occur under the water level and there is no control over related flow and ice parameters. Modelling these processes in the laboratory can provide valuable information in this area.

Ice modelling materials such as doped ice and wax "ice" are available but the majority does not suit the ice jam application. These materials have been used mainly in studies which deal with activities in the Arctic. The doped ice requires a large refrigeration unit and its multi-layered structure presents a problem when the ice sheet is expected to restrain the advancing ice floes. The wax synthetic ice on the market is proprietary, and publications of its properties and handling procedures have been rather limited thereby making an assessment of its suitability to ice jam applications very difficult.

This report outlines the progress made to date on the development of a new synthetic plaster-type model ice called SYG-ICE. In the following section, the desired properties are derived from an examination of the laws of similitude as applied to ice modelling. Because full simulation of all properties is not possible, the important properties pertaining to ice jam testing have to be identified and modelled as best as possible. Following a review of past and present model ice materials, the SYG-ICE material is introduced in a section which contains a description of its preparation and an examination of its properties. The values of the properties are reasonable when compared to those of scaled natural freshwater ice and those of other modelling materials. The report also contains brief descriptions of preliminary studies which involve the use of SYG-ICE in ice cover - ice jam interactions.

2.0 LAWS OF SIMILITUDE

The laws of similitude relate the forces of the prototype to those in the model and the resulting analyses define the ideal properties of the model ice. The laws for ice modelling have been presented by a number of authors (Michel, 1970, 1978; Kotraset _et_ _al_., 1977; Schwarz, 1977; Vance, 1975; Atkin, 1975; Lewis and Edwards, 1970; White and Vance, 1967; Nogid, 1959) and they can be derived by assuming complete similitude in the mechanical model and comparing the applied forces in the prototype and the model.

A number of conclusions can be drawn from such an examination, as summarized in point form below:

(a) The dynamic scale factor, λ_d, should be equal to the cube of the geometric scale factor, λ. That is,

$$\lambda_d = \lambda^3 \tag{1}$$

where $\lambda = L_p/L_m$

$\lambda_d = F_p/F_m$

L and F are length and force and the subscript p refers to the prototype, while the subscript m refers to the model.

(b) If water is used in the model, the density of each material in the model should be equal to the density of the material it represents in the prototype. In this application, the density of the model ice should be equal to the density of natural ice (i.e., λ_ρ = density scale = 1).

(c) Froude similitude should be satisfied. That is,

$$(Fr)_p = \frac{V_p}{\sqrt{gL_p}} = (Fr)_m = \frac{V_m}{\sqrt{gL_m}} \tag{2a}$$

where g = acceleration due to gravity

and V = velocity

$$\text{or} \quad \lambda_k = \sqrt{\lambda} \tag{2b}$$

where λ_k = kinematic scale factor = V_p/V_m.

(d) For water friction forces, the relative roughness should be the same in the model as in the prototype. The Reynolds number should be sufficiently large so that the flows are "fully rough".

(e) If brittle failure is assumed, the ratios of the shear strength, τ, the compressive strength, σ_c, and the flexural strength, σ_f, in the prototype to the same strength in the model are equal to the geometric scale factor. This can be written in the mathematical form as

$$\frac{\tau_p}{\tau_m} = \frac{(\sigma_c)_p}{(\sigma_c)_m} = \frac{(\sigma_f)_p}{(\sigma_f)_m} = \lambda \qquad (3)$$

The geometric scale factor, λ, is also equal to ratios of the rigidity moduli, G, the elastic moduli, E, and the characteristic lengths, ℓ, and this fact can be written as

$$\frac{G_p}{G_m} = \frac{E_p}{E_m} = \frac{\ell_p}{\ell_m} = \lambda \qquad (4)$$

Equations (3) and (4) can be combined to produce a form which is frequently seen in the literature. That is,

$$\frac{E_p}{(\sigma_f)_p} = \frac{E_m}{(\sigma_f)_m} \qquad (5)$$

(f) In order to properly model the cracking activity on the ice cover, the critical stress intensity factor K_{1c} which reflects the fracture toughness of the material should be related by (Atkin, 1975)

$$\frac{(K_{1c})_p}{(K_{1c})_m} = \lambda^{3/2} \qquad (6)$$

(g) In order to model the friction forces of ice on materials other than water, the static and dynamic friction coefficients on both surfaces should be the same in the model as in the prototype.

(h) For surface tension effects, the ratio of the surface tension in the prototype to that in the model should be equal to the square of the geometric scaling factor, λ. The Weber number similitude would then be satisfied.

Ideally, the model material should possess the properties noted above in order to maintain geometric, kinematic and dynamic similarity between the model and the prototype. However, this is very difficult to achieve and, therefore, it is imperative to identify the dominant processes in the specific application and determine the most important properties of the model material. For example, in ice breaker tests, the important properties of the model ice are the friction coefficient (ice on ice, ice on ship's hull), flexural strength and elastic modulus because they influence the breakage of the ice sheet, the size of the broken floes, and the resistance force on the ship. On the other hand, in ice jam tests, it is important to model the density of the ice, ρ_i, as closely as possible because it is critical in determining the level at which the ice sheet will float in the channel. This affects the ability of the cover to restrain the downstream movements of the ice floes and aid in the creation of a jam. It also affects the amount of overtopping at the upstream edge of the ice sheet because partial flooding may augment the bending moments in the cover (Kerr, 1985). A small discrepancy in the density of the model ice could cause a significant change in the floatation level because the latter depends on the difference of the density of water and the ice (ρ_w-ρ_i), approximately equal to 0.08 g/cc. Field observations have shown that although some crushing of the ice sheet does occur in nature, the main mode of fracture is by flexure. Therefore, the flexural strength and the elastic modulus of the ice should be simulated as well as possible because they determine whether the jam would be stable or continue to advance downstream. The characteristic length and the size of the broken floes are also dependent on the flexural strength and elastic modulus.

The internal friction of the ice floes is important in determining the size and shape of an ice jam and the friction coefficient of the blocks in the model should be the same as that in the prototype. However, in the proposed ice jam tests, the ice jam accumulation would comprise of mostly polyethylene blocks with only a small amount of blocks made from the model material. Therefore, the frictional coefficients of the model material (model ice on model ice, model ice on polyethylene) is not a dominant factor in these type of tests.

Another problem in ice modelling is that the properties of the natural ice vary depending on such factors as ice temperature and ice type. However, if average values of these properties are assumed and the geometric scaling factor is given, then the ideal properties of the model ice material can be determined. For example, if for natural ice, $(\rho_i)_p = 0.920$ kg/m^3, $(\sigma_f)_p = 800$ kPa, $E_p = 2000$ MPa, then for $\lambda = 35$, then the properties of the model ice material should be as follows, $(\rho_i)_m = 0.920$ kg/m^3, $(\sigma_f)_m = 23$ kPa, $E_m = 57$ MPa, $E_m/\sigma_{fm} = 2500$. Ideal values of other properties such as uni-axial compressive strength and fracture toughness can also be determined in a similar manner.

3.0 MATERIALS USED FOR ICE MODELLING

Materials used in ice modelling may be divided into two categories: breakable and non-breakable. Non-breakable materials are used to represent ice floes in the simulations of ice jams and other types of ice accumulations. Breakable materials are used more frequently in tests which involve ice-structure interaction, ice breaking process, or breakup initiation of ice cover. The breakable material usually represents the ice cover.

A number of different types of non-breakable materials have been used in the past. These include polyethylene, polypropylene, wood and paraffin. The important properties of these materials are density, surface friction and surface tension. As noted in the previous section, the density and the friction factors of the model ice should be equal to those of natural ice, while the surface tension of the model ice should be equal to the surface tension of natural ice divided by the square of the geometric scale factor, λ. The surface tension of plastics such as polyethylene is usually too high, and has an effect on the "flipping" action of the floes in an ice jam (Ashton, 1974). This factor should be taken into account when using plastic blocks. In past works, Carstens (1968) used a hydraulic model in the design of a power plant intake which should withdraw only the liquid phase of a slush-laden river in Iceland. Polyethylene shavings were used to represent the thick frazil flocs. In another study, Wong et al. (1983) created jams with polyethylene blocks and studied the resulting surges when the jams released.

Use of breakable ice materials started in the late 1950's when a weakened ice was produced by freezing water with a high salt content (1 to 2%). The "doped" or "refrigerated" ice was used to test the interaction between ice and structures (Shvayshetyn, 1957). The main disadvantages with this ice are its low elastic modulus, its low E/σ_f ratio, and the corrosive nature of the salt water.

More work was done on "doped" ice in the 1970's and 1980's. A technique was developed where water of a lower salt content (0.6%) was frozen and then warmed up or "tempered" to produce a weakened material (Schwarz, 1977). Reasonable E/σ_f ratios were obtained, but only for high flexural strengths. Timco (1978, 1980) looked at the possibility of using other types of dopants and found that urea (or carbamide) doped ice had more favourable properties than saline ice. The E/σ_f ratio was above 2000 in most samples and the urea solution did not corrode the pumping equipment.

The main disadvantage with urea and saline ice is their two-layered structure. The bottom layer has a columnar structure while the upper layer is thinner and comprised of much shorter columns with mixed c-axis orientation (Hirayama, 1983). The thickness of the top layer usually varies between 20% and 50% of the total thickness, and the concentration of the brine is usually half of that in the bottom layer. Most of the strength is in the top layer and at low strength ($\sigma_f \leq 30$ kPa), the lower layer is very weak and almost at the point of candling. The two-layer structure presents a problem for ice jam modelling because the ice cover would not be able to restrain the ice accumulation and in so doing create an ice jam. Instead, the advancing ice floes would tend to shear off the weaker lower layer, slide under the cover and continue to be dragged downstream by the water current. Another difficulty might be in correctly reproducing bending fracture and size of fragments.

Recent research on doped ice have produced two uni-layered types of ice, the WARG-fg ice (Enkvist and Makinen, 1984) and the EG/AD/S ice (Timco, 1986). The developers reported properties which are better than existing model ice, but their tests were done on moderately thick samples, 22-40 mm for WARG-fg ice and 40 mm for EG/AD/S ice. It was not reported whether the same results can be achieved in thinner samples.

Synthetic materials have also been used to model the breakable ice sheet. One type of synthetic ice can be made by pouring a hot wax mixture on the water surface and allowing it to cool in place. This type of ice was used at the British Hovercraft Corporation in England to study the performance of ice breakers (Cargo et al., 1970). The ice has a high flexural strength and a high friction coefficient. Michel (1969) modified the mixture by adding several other compounds in order to bring the flexural strength and the elastic modulus to within suitable ranges. The product called MOD-ICE is a proprietary mix and publications on its properties and handling procedures are limited (Schultz and Free, 1984).

Another type of synthetic ice was produced by Tryde (1975). This material has a plaster of paris base with other ingredients added in order to reduce the strength. The paste is placed in a mold and, after setting, the solid sheet is transferred into the test basin. The specific gravity is 0.94, while the flexural strength is 100-200 kPa and the compressive strength is 500-1000 kPa. The high flexural strength dictates a small geometric scale factor and a large model. Tryde used this material in the study of ice forces acting on a inclined plane.

Synthetic material has two advantages over doped ice. First, there is no need for a refrigeration unit which is very expensive to purchase and operate. Secondly, in a cold environment, thermal phenomena may take place and interfere with hydro-structural processes in a manner that is difficult to predict and control.

4.0 SYG-ICE

SYG-ICE is a synthetic material being developed for use in ice jam scale modelling. The material is made from a plaster mixture (similar to Tryde's) and possesses properties which are reasonably close to those defined by the laws of similitude at fairly large scaling factors. The preparation, testing and properties are presented in the following sections.

4.1 Preparation of SYG-ICE

The plaster mixture comprises varying proportions of PVC resin, light exterior stucco, plaster of paris, glass microbubbles and water. The powdered ingredients are first mixed dry and then water is added to produce a paste of runny texture. The paste is then poured and trowelled into a mold lined with wax paper and the paste is allowed to cure under a burlap cover for a period 10 to 14 days during which time it solidifies into a sheet. The mold holding the ice sheet is transported to the test flume and placed on levelled supports (Figure 1). The water level in the flume is raised very slowly and the sheet is soaked and allowed to gently float off the mold. The wax paper is stripped as the ice sheet is pushed away from the mold (Figure 2). The water level is lowered, the mold and supports are removed and the solid ice sheet is then ready for testing. The special procedure outlined here is necessary because of the low strength and small thickness of the sample. Detailed preparation techniques are described in Wong et al. (1988).

As expected, the properties of the material are dependent on the proportions of the ingredients. The standard formula below notes the amount of each ingredient as a portion of the polyvinyl chloride resin which is listed as 1.000.

Standard Formula

1.000	polyvinyl chloride resin;
0.161	light exterior stucco;
0.043	plaster of paris;
0.100	glass microbubbles; and
1.051	water.

Each ingredient contributes to the overall properties of the material. The PVC resin acts as the filler and occupies the most volume in the mixture. The resin comes in the form of small grains and its density is slightly less than 1.000 kg/m^3. The exterior stucco acts as the binding component while the plaster of paris acts as a weakening agent. It is possible to obtain a material of the same strength by using no plaster of paris and substantially less stucco but the surface of this material would be rougher and more grainy. Microbubbles are small glass spheres with air trapped inside, and are used to control the density of the material. Water is generally added last and its amount may depend on the texture of the final paste or it may be specified beforehand in the ingredient list.

4.2 Testing SYG-ICE

Each ice sample is subjected to a number of standardized tests which measure the density, flexural strength and elastic modulus. The Density test, the 3-Point test and the Simple Beam tests are performed on small beams which measure approximately 30.0 cm x 4.0 cm x 1.5 cm. The fourth test, the Pull-Up test, is performed on the entire ice sheet and is destructive. For this reason, the Pull-Up test was done only on a limited number of ice sheets.

The Density test determines the density by simply weighing a thoroughly wetted beam whose dimensions have been measured by a vernier. The beams can be removed from the water and therefore in-situ measurements are not necessary.

The Simple Beam test determines the range of the flexural strength. In this test, a small beam measuring approximately 30.0 cm x 4.0 cm x 1.5 cm is placed across two supports spaced several centimetres apart (Figure 3). If failure does not occur then the beam is removed and the distance between the supports is increased by one centimetre. The process is repeated until the beam fails. The density and dimensions of the beam are measured and the distance between the two supports are also noted. Taking into account the overhanging length at each end, flexural strength values are calculated for the case just before failure and the case at failure. This defines a small range in which the actual flexural strength lies.

In the 3-Point test, the beam is supported at the ends and loaded in the middle by a motorized drive shaft. The load cell connected to the shaft measures the force while a linear differential variable transformer (LVDT) measures the deflection of the beam (Figure 4). The shaft moves down at a speed of 0.12 cm per second. The data are recorded by a computer, and a plot of applied force versus deflection can be produced (Figure 5). Taking into account the weight of the beam, the bending strength and the elastic modulus can be calculated.

In the Pull-up test, the ice sheet is allowed to float in a basin. An aluminum bar placed under the front edge is pulled up by means of a string connected to the load cell and the drive shaft (Figure 6). It is assumed that the water acts as an elastic foundation and that the sheet is sufficiently long to respond as a semi-infinite plate. By considering the maximum moment through the sheet (Hetenyi, 1944), the elastic modulus and the flexural strength can be calculated from the force at failure and the dimensions of the broken piece. More detailed description of this and the other three tests are presented in Wong _et_ _al_. (1988).

4.3 Properties of SYG-ICE

Density, bending strength and elastic modulus were routinely tested during the development of the SYG-ICE material. "Ball-park" values of other properties of the standard formula material were determined in a series of tests performed at the National Research

Council's Hydraulics Laboratory. These properties include the uniaxial compressive strength, shear strength, fracture toughness, and friction coefficient. The values of these properties are regarded as estimates because the number of tests were few and in many cases the dimensions of the samples were not ideal for the testing equipment at that facility.

The properties of the SYG-ICE material are listed in Table 1 together with the properties of natural freshwater ice and other model ice materials. Past ice surveys and tests have shown that the properties of natural ice are not constant, but depend on a number of factors which include size of sample, method of testing, temperature of ice sample, and rate of loading (Gow et al., 1978; Labrov, 1971; Nadreau and Michel, 1984). Needless to say, field values spread over a wide range and, in order to avoid confusion, only one "typical" value for each property is quoted in Table 1. This table serves to provide a general impression of the suitability of SYG-ICE as a modelling material. Direct comparisons of specific property values are not meaningful because methods of testing may differ among research centres and, for some ice types, the properties of the material may be dependent on the dimensions of the samples.

SYG-ICE has reasonably good properties even though the ice sample thickness was only 15 to 17 mm. It is not known at this time if samples with different thicknesses would appear to have different material properties. Although the material is homogeneous, there may be scale effects if different sample sizes are tested.

The density of SYG-ICE material at 900 kg/m^3 is very close to the density of natural freshwater ice, which is 920 kg/m^3 or less as air content increases (Nadreau and Michel, 1984). As mentioned earlier, density is important in ice jam modelling because it determines the level at which the ice sheet floats and this affects how it interacts with the oncoming ice floes and water flow. If desired, the density of SYG-ICE material can be changed by adjusting the proportion of glass microbubbles in the formula.

The flexural or bending strength of the standard SYG-ICE material was found to be 23 to 28 kPa by the simple beam test, 26 kPa by the 3-Point test, and 25 kPa by the Pull-Up test. If the strength of the prototype ice is assumed to be equal to 800 kPa, then a geometric scale factor of 30 to 40 can be used. The strength can be readily decreased (or increased) by subtracting (or adding) more of the binding agent to the formula. Reduction in the strength allows a larger scale factor but handling of the weaker material would become more difficult (see also Wong et al., 1988, for a discussion of property variations caused by changes in the standard formula).

Field work has shown that 3-point loading techniques yielded strength values which are higher by a factor of 1.2 to 1.7 than those measured by cantilever beam methods (Gow et al., 1978). It has been suggested that the cantilever beams break with lower applied forces because of the stress concentrations at the corners of the outstretched beam or because of the reduction in transverse forces in the cantilever case (Labrov, 1971). In comparing flexural strengths in Table 1, it should be noted that the strength of SYG-ICE is not based on the cantilever technique and thus may appear higher than would have been the case with the cantilever-type of test which has been commonly used for other materials.

Brittle-type failures occurred in the bending tests and there was no residual strength after the initial break. This can be seen in a typical plot of force versus time in a 3-Point test in Figure 5 where the force on the loading shaft quickly falls to zero after the beam broke. In fact, the beam falls away from the loading shaft in most tests.

Elastic modulus values were determined by two methods; the 3-Point test and the Pull-Up test. The value from the Pull-Up test is approximately three times larger than that from the 3-Point test (Wong et al., 1988). There is some uncertainty in the 3-Point test because the small beam used in the test typically deflects only 0.20 mm before failure occurs, but the deflection measuring device (LVDT) cannot be calibrated in this low range. Larger deflections cannot be obtained by using longer beams because fracture would occur due to the weight of the beam alone. More reliable results are obtained from the Pull-Up test which does not require deflection measurements but relies on the location of the bending crack (Wong et al., 1988). A similar finding is noted in Enkvist (1984) when comparing the elastic modulus derived from a 3-point loading test to the modulus derived from the Plate method. The Plate method involves loading the center of a floating ice sheet and recording the deflection of a point immediately adjacent to the load. The characteristic length and the elastic modulus can be calculated from these measurements (Sodhi et al., 1982). In general, it was found that the Plate method also yielded results which are 1.2 to 2.5 times higher.

The elastic modulus of SYG-ICE was found to be 28.7 MPa by the 3-Point method and 95.6 MPa by the Pull-Up test giving a ratio of elastic modulus to flexural strength of 1,110 and 3,870, respectively. The values are above and below the prototype value of 2,500 and therefore it may be wise to test the material by the more widely used Plate method in the future in order to determine which ratio is closer to the desired value.

The uni-axial compressive strength is important if the crushing mode is dominant and if forces exerted by the ice cover on a structure are to be modelled. Table 1 shows that this property would be properly scaled since the horizontal compressive strength of SYG-ICE was about 62 kPa which is 30 to 40 times smaller than the prototype value. The ratios of the uni-axial compressive strength and the flexural strength are also comparable.

Fracture toughness is a property of the ice material that reflects the ability of a crack to grow in the ice cover. It is measured in terms of the critical stress intensity, K_{1c}, and previous measurements on freshwater ice range from 60 to 300 kPa $m^{1/2}$ (Urabe and Yoshitake, 1981). Using a geometric scale factor, λ, of 35, the value of the critical stress intensity for the model ice should range between 0.3 and 1.5 kPa $m^{1/2}$ (see Eq. 6). The critical stress factor of 2.2 kPa $m^{1/2}$ for SYG-ICE at this scale is outside the range. Thus, the propagation of a crack in the model cover would be slower than in nature, but this seems to be true of other model ice materials as well. It is unknown whether progression of a crack is an important mode of breakage in breakup processes, but if it is, the critical stress factor can be reduced by increasing the flexural strength of SYG-ICE, thereby reducing the geometric scale factor.

When compared to the friction coefficient of natural ice, the SYG-ICE static friction coefficient of 0.50 is reasonable, but the dynamic fraction of 0.50 is considerably high. This would be a problem in ice-breaking modelling, but it is much less significant in ice jam modelling because the majority of the broken ice accumulation would consist of polyethylene blocks and it is the internal friction of these blocks which should closely match the friction coefficient of natural ice.

5.0 APPLICATIONS OF SYG-ICE

SYG-ICE was used to investigate the creation of transverse cracks caused by advancing flood waves. In theory, the ice cover is subjected to bending on the vertical plane owing to the shape of the water surface. Breakage is dependent on the shape and the size of the incoming wave (Beltaos, 1985). In the laboratory, the SYG-ICE sheet measuring 2.5 m x 0.98 m x 0.15 m was placed in the 1 metre flume and a small discharge of water was allowed to flow through the flume. A gate upstream of the sheet was lowered in the flume thereby raising the water level upstream. The gate was then lifted and a wave was generated and moved downstream past the ice sheet. The wave action on the sheet was recorded by video cameras and the stage at a number of points along the flume was measured by wire gauges and pressure transducers. Figure 7 shows the deflection of the ice sheet as a wave passed. The edge of the SYG-ICE sheet was painted so that it would be easier to see. Progressively larger waves were generated until cracks developed in the sheet. Descriptions of these tests are forthcoming in another report.

In another series of tests, it was examined if the SYG-ICE sheet could restrain an advancing ice accumulation and create a jam. Polyethylene blocks were packed behind a vertical lifting gate just upstream of the ice sheet and the discharge was held constant. The gate was then raised and the ice blocks moved downstream, preceded by the water surge. The latter caused overtopping on the upstream edge of the sheet and after it had passed, the blocks advanced onto the ice sheet breaking off pieces as they moved. Eventually, the blocks were restrained in most cases and a jam which may be grounded in some places was formed. Figures 8a and 8b show the side and top views of a jam held in place by the ice sheet. The sizes of the broken SYG-ICE pieces are consistent with those of floes observed in the field. In cases where the initial backwater was large, the water surge would create a series of transverse cracks in the cover and submerge and transport the resulting floes before the polyethylene blocks arrived.

6.0 CONCLUSIONS

The development of SYG-ICE was motivated by the need for a non-refrigerated model ice material which will adequately simulate the behaviour of the natural ice cover in ice jam processes. This enables studies of hydraulic processes in the laboratory where the flow and ice parameters can be controlled and where data collection is relatively easy.

SYG-ICE is a synthetic material, made from a plaster mixture of polyvinyl chloride resin, light exterior stucco, plaster of paris, glass microbubbles and water. The hardened sheet is homogeneous and its mechanical properties are satisfactory. With samples of 15 to 17 mm thickness, the standard formula ice has a flexural strength of approximately 25 kPa and an elastic modulus-flexural strength ratio between 1110 and 3360. Bending fracture is brittle and there is no residual strength after failure has occurred. The density of 900 kg/m^3 is very close to that of natural ice and if required it may be changed by adjusting the proportions of the glass microbubbles. In fact, the flexural strength and other properties may be altered by changing the standard formula. Less extensive, supplementary tests have produced acceptable values of less "critical" properties such as fracture toughness, uni-axial compressive strength and friction coefficients.

The material has already been used in flume tests to examine the fracture of the cover by advancing flood waves and the formation of a jam caused by the intact ice cover. In both studies, the model ice performed satisfactorily and results of these tests are forthcoming.

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Table 1. Approximate Properties of Natural Ice and Model Ice Materials

Ice Type Property	Natural Ice	Standard SYG-ICE	Urea Ice	WARC-FG T-1	EG/AD/S	MOD-ICE	Plaster of Paris
Thickness Tested (mm)	varied	15 - 17	40 - 50	22 - 40	40	12 - 60	
Specific Gravity	0.92 or less	0.90	0.95	0.95 (assumed same as Urea Ice)	0.95 (assumed same as Urea Ice)		0.94
Flexural Strength (kPa)	800	22.7 - 28.4	10 - 80	13 - 28	20 - 110	10 - 80	100 - 200
Elastic Modulus (MPa)	2,000	28.7 (3-Pt) 95.6 (Pull)	30 - 180	7.9 - 27.9	50 - 300	11 - 70	100
El. Modulus / Flex. strength	2,500	1,110 (3-Pt) 3,870 (Pull)	2,000 - 2,500	1,000 - 1,366	1,100 - 2,600	700 - 6,000 most <1,500	500 - 1,000
Compressive Strength (kPa)	3,200 (vert.) 2,300 (horiz.)	61.9 (h)	120 - 250 (v) 75 - 160 (h)	50 - 400 (v)	150 - 370 (v) 80 - 280 (h)	12 - 82 (h)	500 - 1,000 (h)
Compr. str. / Flex. str.	4.0 (vert.) 2.9 (horiz.)	2.5 (h)	3 - 6 (v) 2 - 6 (h)			0.6 - 2.3 (h)	
Shear Strength (kPa)	600 (vert.) 600 (horiz.)	6.8 (v)	30 - 70 (v) 35 - 65 (h)				250 - 500 (v)
Friction Coefficient (ice on ice)	0.70 (stat) 0.12 (dyn)	0.50 (stat) 0.50 (dyn)	0.35 (stat)				
Fracture Toughness (kPa-$m^{1/2}$)	150	2.2	4 - 16		2 - 13		
Sources	Labrov (1969) Urabe and Yositake (1981)	Wong et al. (1988)	Timco (1980) Timco (1985)	Enkvist (1984)	Timco (1986)	Schultz and Free (1984)	Tryde (1975)

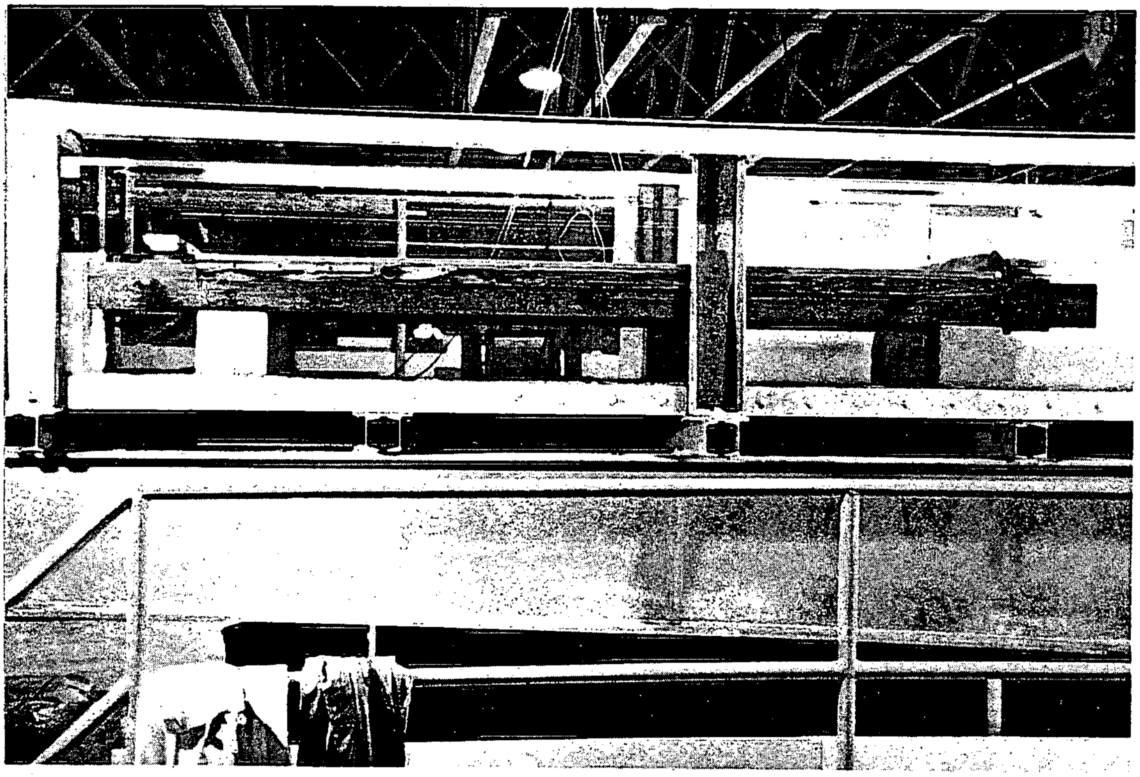

Figure 1 Placing the mold in the test flume

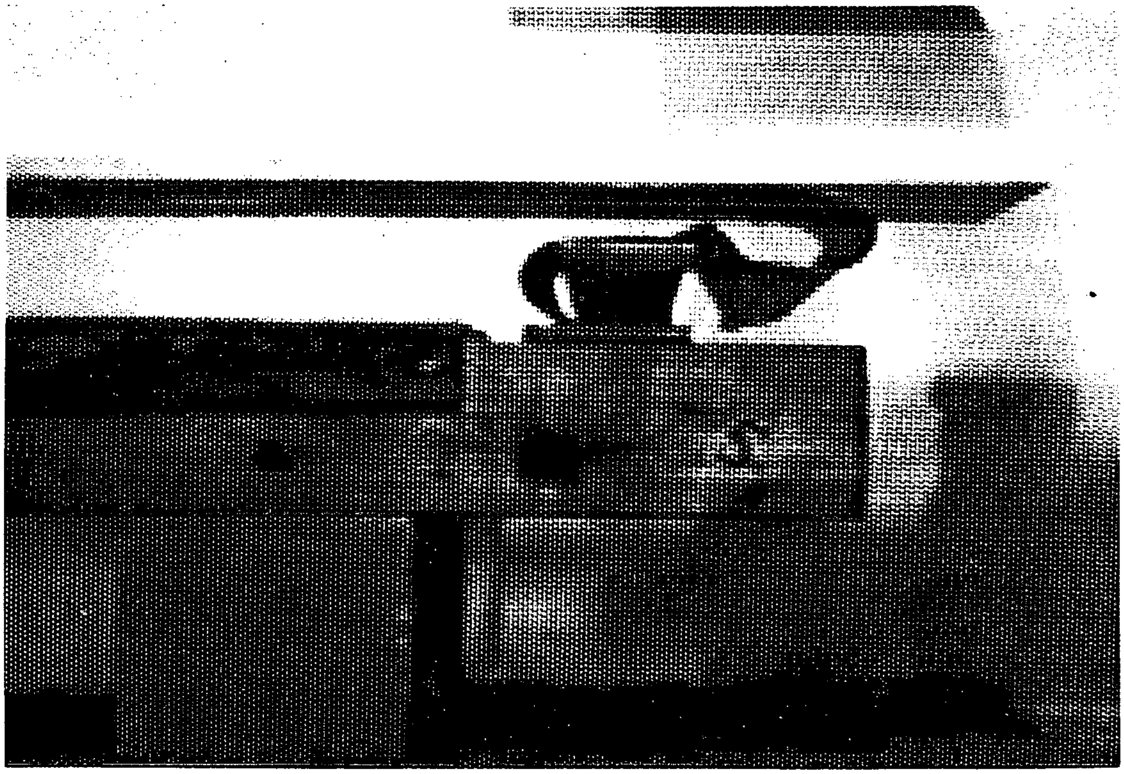

Figure 2 Removing SYG-ICE sheet from its mold

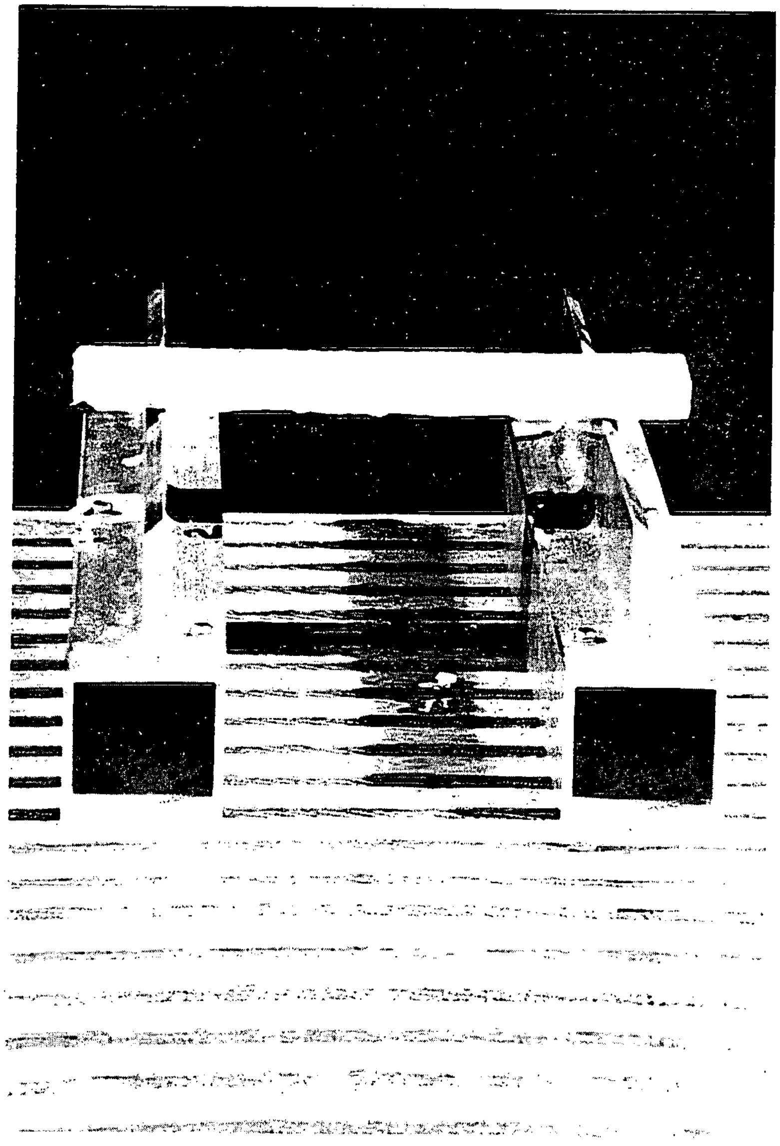

Figure 3 The simple beam test

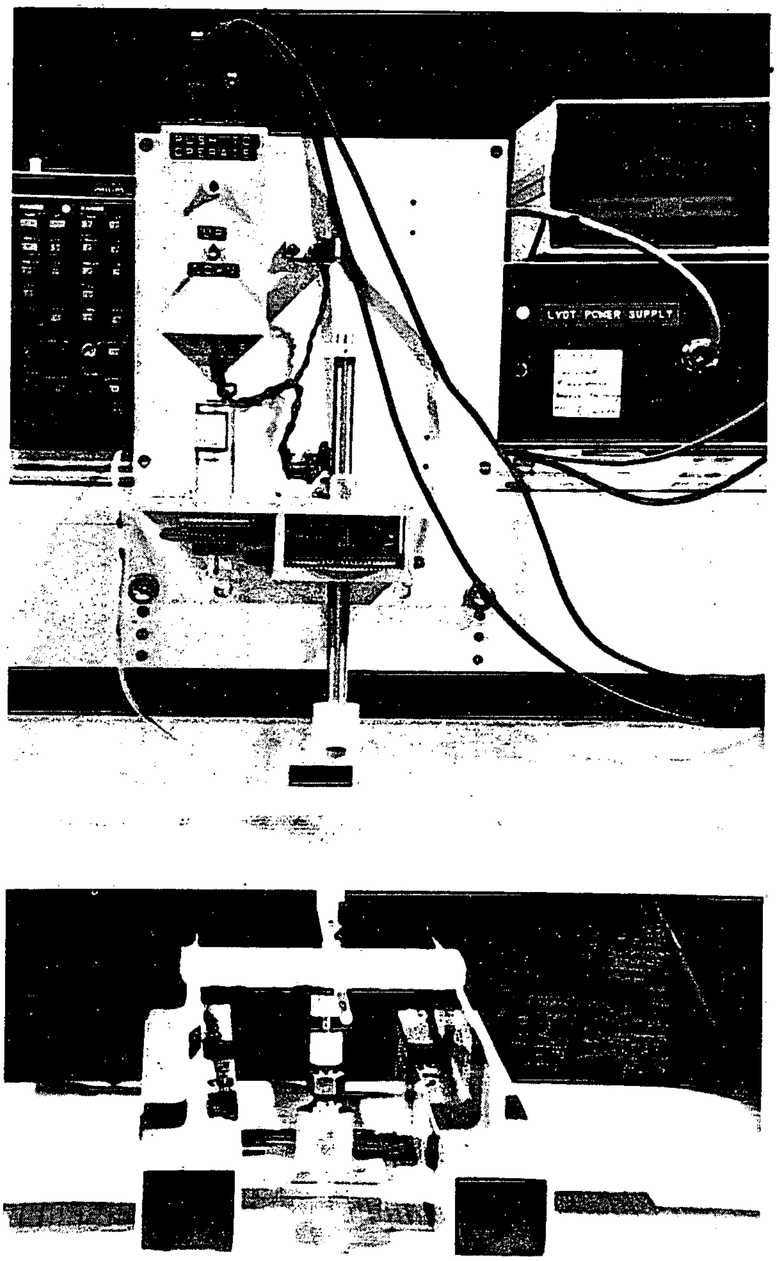

Figure 4 The 3-Point test

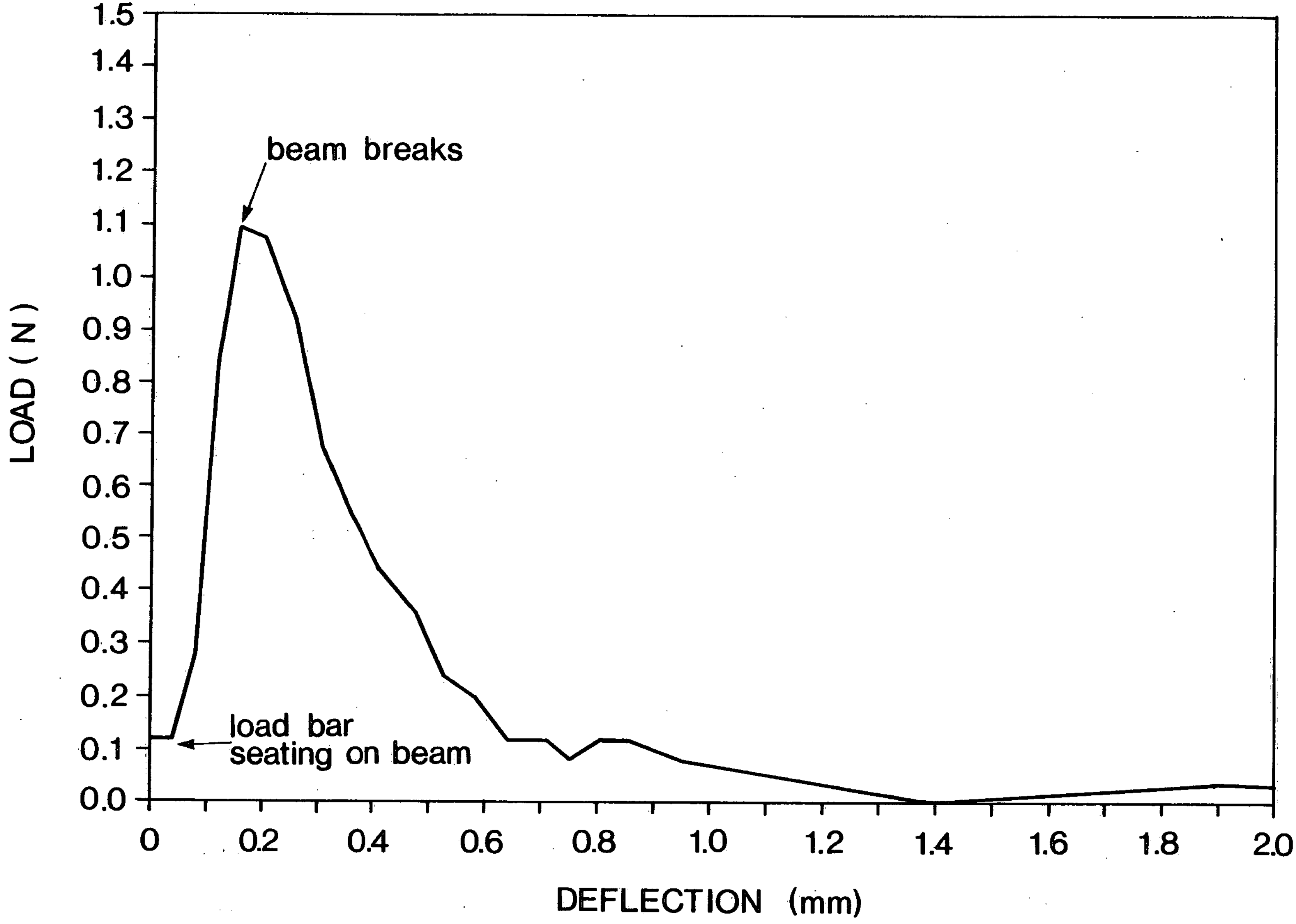

Figure 5 3-Point test - Load vs Deflection

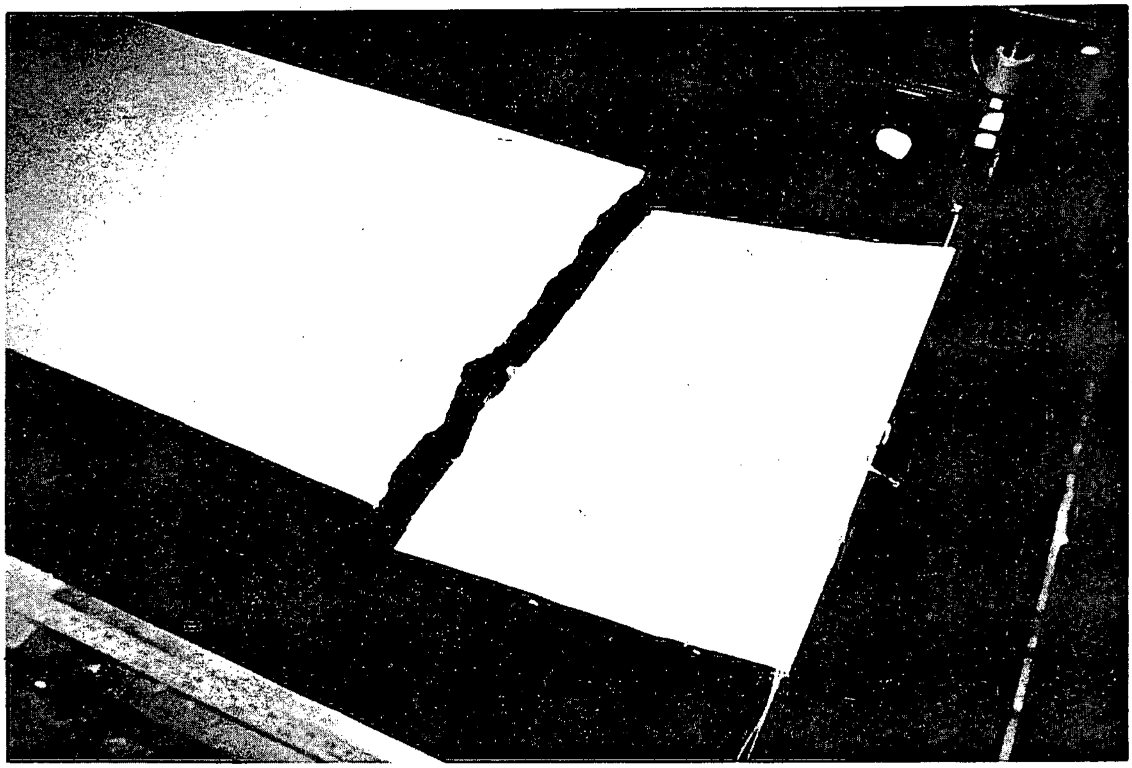

Figure 6 The Pull-up test

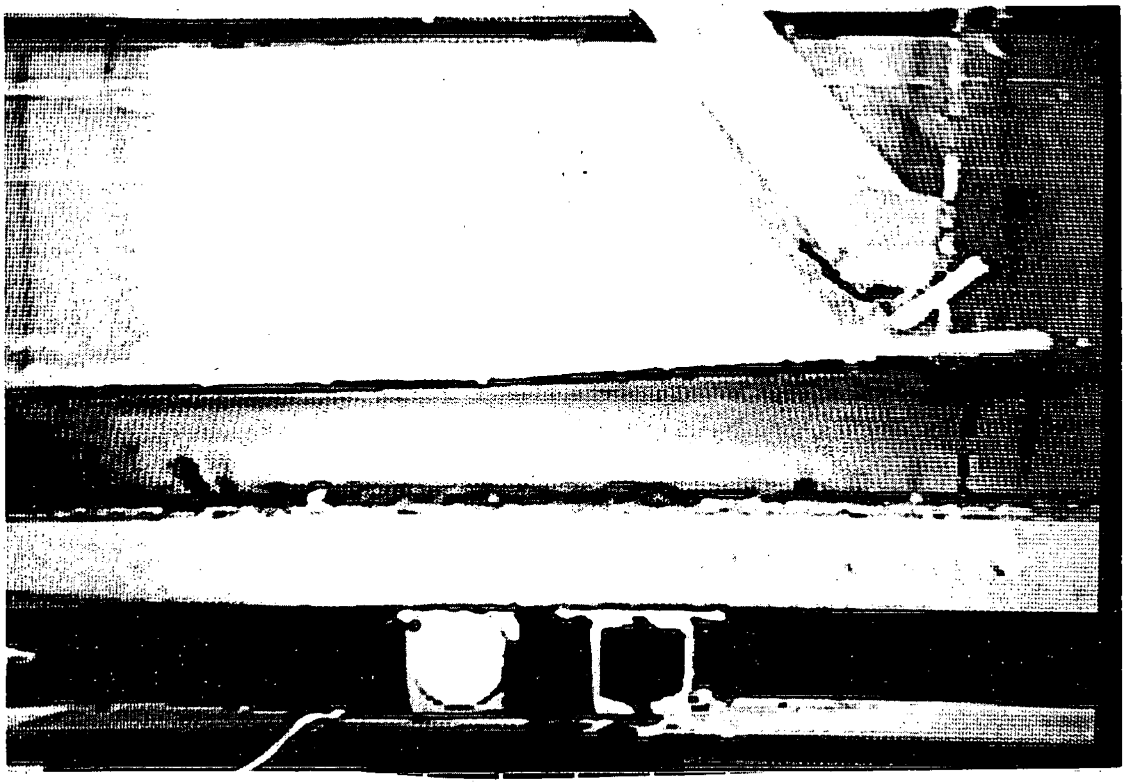

Figure 7 Deflection of SYG-ICE sheet by an advancing wave

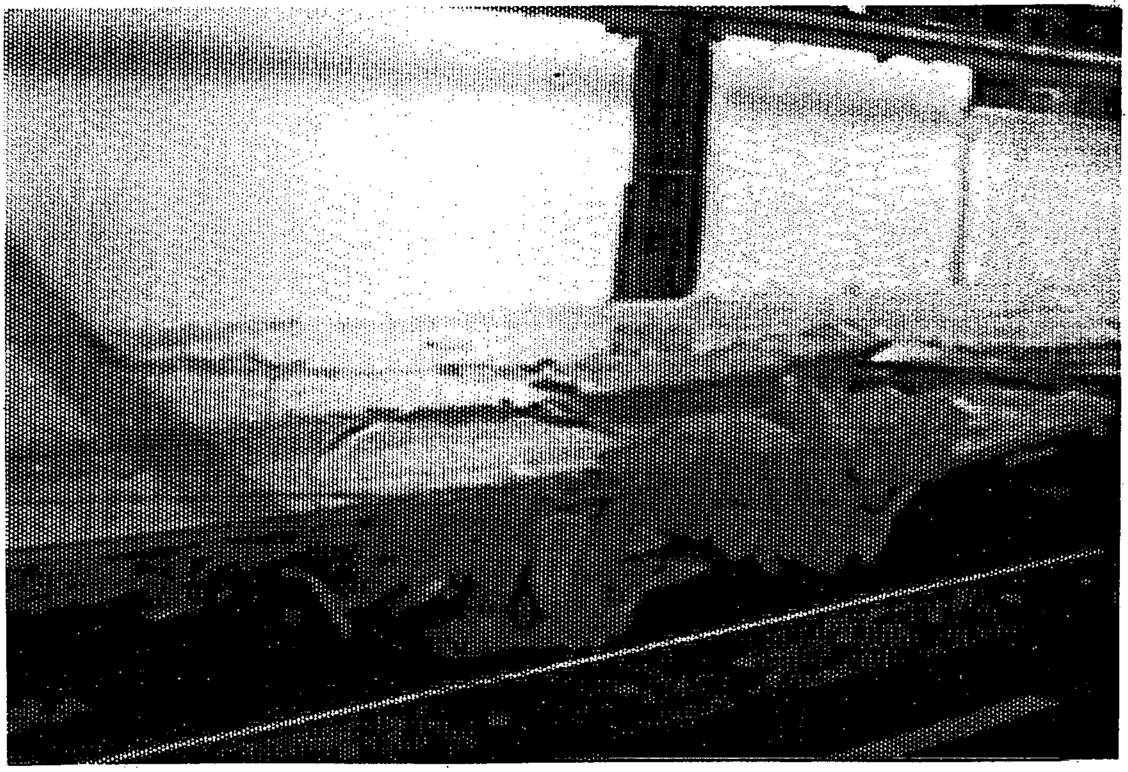

Figure 8a Side view of ice jam restrained by SYG-ICE sheet

Figure 8b Close up top view of Ice Jam restrained by SYG-ICE sheet
Note-broken SYG-ICE floes in ice accumulation