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A MODEL MATERIAL FOR RIVER ICE BREAKUP STUDIES

by

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ABSTRACT

Laboratory simulation of river ice breakup processes would enable control of ice and flow conditions and permit observation of important phenomena which, in nature, take place under water. A synthetic material with properties suitable for laboratory studies of breakup and related phenomena has been developed recently. This material is fine-grained, needs no refrigeration, and its properties compare well with those of existing materials, used mainly to model ice-vessel and ice-structure interactions. The new material performed satisfactorily in two test series, designed to test the interaction of water waves and ice jams with the intact sheet ice cover.

MANAGEMENT PERSPECTIVE

River ice jamming and associated flooding are partly governed by little known processes of fracture and breakup of the ice cover. An important research avenue is testing in the laboratory where various parameters and conditions can be controlled. Such work is hindered, however, by a dearth of suitable materials that, under typical laboratory-scale reductions, will adequately simulate the fracture of the natural ice cover. A model material having the appropriate properties is described. It is grainy, single-layered and made of a plaster-based mixture. There is no need for refrigeration which avoids expense and possible complications due to unwanted thermal effects.

Two series of tests have been performed with the new material, designed to study the interaction of water waves and ice jams with the intact sheet ice cover of a river. The material performed satisfactorily while a need for more experiments to elucidate the various breakup processes was indicated.

INTRODUCTION

Major advances in understanding river ice breakup and jamming processes can be made if the associated phenomena are reproduced and studied in the laboratory. Flow and ice conditions can change rapidly in the field, quantitative data are not easily obtainable and much happens under the water surface where it cannot be observed. River breakup involves three types of processes, hydraulic, thermal, and structural. The first two are understood to some degree but very little is known about the third type, despite its obvious importance in such questions asbreakup initiation, formation of ice jams, and advance of ice runs.

Todate, very few laboratory studies of ice breakup have been performed (1, 2). This reflects the general lack of materials that can adequately simulate the fracture of an ice sheet under laboratory scale reductions. To address this gap, a synthetic material has been recently developed at the National Water Research Institute of Canada. It is a non-layered, fine-grained material that can be used at room temperature. The material, called SYG-ICE, is described in the next sections along with two series of test runs performed with it.

REQUIRED PROPERTIES

For typical laboratory scales relative to rivers (20-40), the laws of similitude can be used to derive the properties of a model-ice material, as has already been done by many authors (3).

Since water is to be used in the "model", the density scale equals 1.0 so that the model ice must have a density equal to that of real ice. Strength scales can be shown to be equal to the geometric scale, λ; and the same holds for the moduli of rigidity and elasticity. It follows that the ratio E/σ_f (E = mod. of elast.; σ_f = flexural strength) has to be the same in the prototype and in the model. To model the cracking process, the fracture-toughness scale, λ_k should equal $\lambda^{1.5}$. Where applicable, surface tension and frictional effects have to be modelled as well.

Often, it is impossible to attain exact similitude and in practice, focus is placed on those processes that by-and-large determine the outcome of an event or experiment. For river ice breakup, flexure is the main mode of fracture, hence the flexural strength, σ_f is the most important parameter. The modulus of elasticity, E, is also important because it governs ice deformations as well as the sizes of ice fragments. Attention should also be paid to the fracture toughness since this parameter governs the cracking activity. Shear and crushing are known to occur but their effects on the onset and progress of breakup are not major.

Consider an ice cover 45 cm thick, with σ_f = 600 kPa and E = 6 GPa; with λ = 30, the model material should have a thickness of 15 mm, σ_f = 20 kPa and E/σ_f = 10,000. Note the very low but achievable strength and the very high E/σ_f ratio. The latter is very difficult to achieve but some discrepancy is permissible because the size of ice fragments is proportional to the fourth root of E.

MATERIALS USED FOR ICE MODELLING

Several materials are already in use, mainly for model tests of ice breakers or structure-ice interactions. They can be subdivided into refrigerated or "doped" ice and synthetic "ice". In doped ice, low-strength is achieved by introduction of salt or urea and by "tempering", i.e. gradual warm-up (4, 5). A drawback is the two-layer structure of such materials, i.e. a thin, strong top layer and a weak, columnar bottom layer. More recent work has resulted in uni-layered materials such as the WARC-FG (6) and EG/AD/S (7). Doped ice requires extensive refrigeration facilities, not normally available in hydraulic laboratories. Moreover, refrigeration may cause unwanted freezing or thawing in cases where structural and hydraulic processes are being modelled simultaneously. Synthetic materials are more suitable in this regard and can be sub-divided into wax-based, such as the proprietary MOD-ICE (8) and plaster-based (9). The latter is too strong for the present purposes, however (σ_f > 100 kPa).

SYG-ICE

This is a synthetic material, developed at the National Water Research Institute, with the specific intention to use it for studies of river ice breakup. The mixture contains different portions of PVC (polyvinyl chloride) resin, light exterior stuco, plaster of paris, glass microbubbles and water. The powdered ingredients are mixed dry and water is added to produce a paste of runny texture. The paste is poured and trowelled in a mold lined with wax paper and allowed to cure under a burlap cover for 10 - 14 days until it solidifies into a sheet. The mold holding the sheet is then carefully transported to the test flume and placed on levelled supports. The water level in the flume is raised slowly and the sheet is soaked and allowed to gently float off the mold. The sheets produced to date are 0.98 m wide, 2.44 m long and 15 - 20 mm thick.

The properties of SYG-ICE depend on the proportions of its ingredients and the "standard formula" below represents the best combination achieved so far.

"Standard Formula" (by weight)

1.00	PVC Resin
0.16	light exterior stucco
0.04	plaster of paris
0.10	glass microbubbles
1.05	water

The resin, slightly lighter than water, acts as a filler while the stucco and plaster are binding agents. Microbubbles are small glass spheres with air trapped inside, used to control the density of the material.

Density, flexural strength, and elastic modulus are routinely determined by testing thoroughly wetted specimens of SYG-ICE. Measuring density is straight-forward but σ_f and E require more elaborate techniques. A good method is the "pull-up" test in which a floating sheet is fractured by a distributed upward load, applied rapidly very near the edge. This situation can be approximated by the theory of an infinitely long beam resting on an elastic fundation (10). The distance of the transverse crack from the edge defines the modulus E while, from the failure load and E, σ_f can be calculated. Flexural strength was also determined by bending small specimens (30 m long x 4 cm wide) outside of the flume, either by the "simple beam test" or by the "3 - point loading" test. The former consists of increasing the distance between the supports until the specimen breaks under its own weight. The 3 - point loading test includes measurement of deflection as a means of determining E but yields a value about three times less than the pull-up test, possibly due to the very small deflections involved. A similar finding was reported in Ref. (6).

Other properties of SYG-ICE (e.g. compression and shear strengths, fracture toughness, friction) were determined at the National Research Council of Canada where appropriate equipment is available. The values obtained are regarded as estimates because the number of tests were few and, occasionally, the specimen dimensions were not ideal for the testing apparatus.

Table 1 lists the properties of SYG-ICE along with those of existing materials. It is noted that SYG-ICE compares well with other materials and comes close to the "ideal", i.e. a 30-scale model of natural freshwater ice near the time of breakup.

APPLICATIONS

SYG-ICE has, so far, been used in two test series conducted in the 1m flume of the Institute's Hydraulics Laboratory. The first series was a qualitative study of the interaction between a released jam and the intact ice cover downstream while the second investigated ice-breaking by a surge of water.

Ice Jam Release and Re-formation

In this series, it was examined whether SYG-ICE sheets could restrain advancing accumulations of blocks and create a jam, as happens often in nature. Polyethylene blocks were packed behind a gate made of vertical rods, thus forming an ice jam. Downstream of the gate, SYG-ICE sheets were placed to simulate the intact ice cover that usually exists downstream of ice jams. After measuring the configuration of the jam and the water level profile, the gate was lifted and the accumulation of blocks moved downstream, preceded by a surge of water. This surge was usually not steep enough to break the ice as it passed under it. Shortly after, the blocks arrived, causing some local breaking of the sheet but eventually stopped and formed a new jam (Fig. 1). The photo in Fig. 2 shows that the pieces broken off the sheet have dimensions consistent with what is observed in the field. In one case, the initial backwater was so large that the water surge caused a series of transverse cracks in the "ice", submerging and transporting the resulting strips before the blocks arrived.

Wave Breaking

In each test, a solid gate located 2m upstream of an "ice" sheet was lowered into the flume thereby raising the water level upstream to a pre-selected elevation. After measuring the water level profile, the gate was lifted rapidly and the resulting water wave monitored by video cameras and by numerous water-level recording devices (wire gauges and presure transducers) placed along the test reach. The deformed shape of sheet as the wave is passing under it is illustrated in Fig. 3. Progressively higher surges were generated until the sheet fractured.

The characteristics of each surge were determined from the water level records obtained at the gauged sites (e.g. see Fig. 4) and are listed in Table 2, along with other test parameters. The results are in general agreement with theoretical predictions (11, 12). Occasional discrepancies are probably due to different modes of failure from those postulated by the theory. Extrapolation of the present results to rivers indicates that extreme wave slopes (> 0.005) are needed for ice breaking in this manner, an unlikely natural occurrence, except very briefly after the release of a major jam. Therefore, additional fracture mechanisms have to be investigated, a task that can be facilitated by continued use of SYG-ICE.

SUMMARY AND CONCLUSIONS

A synthetic non-refrigerated material has been developed, having properties suitable for laboratory studies of river ice breakup and related phenomena. This material, named SYG-ICE, is non-layered and compares well with other materials used for ice modelling but mostly to simulate ice-structure or ice-vessel interactions. Two series of tests have been conducted with SYG-ICE, simulating the interaction of water surges and ice jams with intact ice covers. The results are encouraging in that SYG-ICE performed satisfactorily but also indicate a need for more experiments to elucidate the various breakup processes.

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Table 1. Properties of model ice materials.

Material / Property	"Ideal"(1) [fresh-water] $\lambda = 30$	Standard SYG-ICE	Urea Ice	WARC-Fine Grain	EG/AD/S	MOD-ICE	Plaster of Paris
Thickness Tested (mm)	N.A.	15-20	40-50	22-40	40	12-60	N.I.(2)
Specific Gravity	0.92	0.90	0.95	N.I.(2)	N.I.(2)	0.70-0.89	0.94
Flexural Strength (kPa)	10-30	23-28	10-80	13-28	20-110	10-80	100-200
Elastic Modulus / Flex. Strength	5,000 to 10,000	3,900	2,000 - 2,500	1,000 - 1,400	1,100 - 2,600	700 - 6,000 (mostly below 1,500)	500 - 1,000
Compressive Strength (kPa) (horizontal)	70	62	75-160	40-400	80-280	12-82	500-1,000
Shear Strength (kPa)	6-20	7	30-70	N.I.	N.I.	7-120	250-500
Friction Coeff.	0.70(stat) 0.12(dyn)	0.50(stat) 0.50(dyn)	0.35 (stat)	N.I.	N.I.	0.45 (stat)	N.I.
Fracture Toughness ($kPa\ m^{1/2}$)	0.4-1.8	2.2	4-16	N.I.	2-13	N.I.	N.I.
Sources	(13,14)	this paper	(5,15)	(6)	(7)	(8)	(9)

(1) A material that will accurately simulate natural river ice near the time of breakup at a geometric scale of 30.

(2) Not indicated in the corresponding sources.

Table 2. Tests on breaking SYG-ICE covers with water surges in 1 m wide flume.

Date of Test	Initial Water Depth (cm)		Discharge (m^3/s)	Surge Properties		"Ice" Properties				Did Cover Break ? (Yes/No)	Theoretical Prediction	
	Upstream	Downstream		Max. Slope	Max. Rise (cm)	σ_f (kPa)	E (MPa)	Thick. (mm)	Spec. Grav.		Billfalk (1982)	Beltaos (1985)
11.12.86*	15.1	11.5	0.011	0.008	2.1	25	60	14	0.92	NO	NO	NO
08.01.87*	20.0	12.0	0.013	0.029	3.0	40	160	14	0.92	NO	NO	NO
13.05.87	15.8	15.0	0.014	0.005	0.3	23	114	18	0.98	NO	NO	NO
13.05.87	17.6	15.0	0.014	0.020	1.0	23	114	18	0.98	NO	YES	NO
13.05.87	19.0	15.0	0.014	0.032	1.7	23	114	18	0.98	YES	YES	YES
17.08.87	23.8	22.1	0.013	0.010	0.9	72	214	16	0.97	NO	NO	NO
17.08.87	25.0	22.1	0.013	0.017	1.5	72	214	16	0.97	NO	NO	NO
17.08.87	26.2	22.1	0.013	0.023	2.1	72	214	16	0.97	YES	NO	NO
19.08.87	11.5	8.9	0.006	0.043	1.0	61	87	19	0.93	YES	NO	NO
25.08.87	11.6	8.3	0.005	0.035	1.3	32	83	20	0.95	NO	YES	NO
25.08.87	13.3	8.3	0.005	0.087	1.9	32	83	20	0.95	YES	YES	YES
21.10.87	16.5	13.3	0.002	0.025	1.5	17	64	16	0.92	YES	YES	YES
23.10.87	13.9	11.0	0.002	0.041	1.9	32	95	16	0.88	YES	YES	YES
24.10.87	19.5	16.0	0.004	0.031	2.3	19	75	18	0.89	YES	YES	YES
08.12.87	21.0	16.1	0.027	0.033	2.7	32	103	16	0.89	YES	YES	YES
09.12.87	22.0	16.1	0.002	0.034	3.0	17	64	17	0.92	YES	YES	YES

* Surges were produced by releases of ice jams.

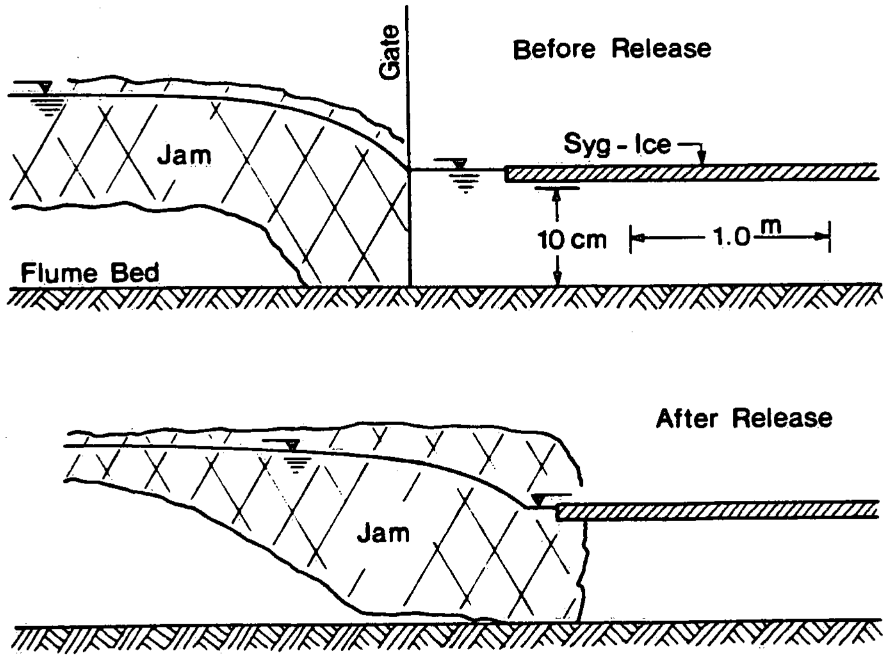

Fig. 1. Configurations of initial jam and jam formed at SYG-ICE edge after release. Test of Jan. 8, 1987. Approx. 0.25 m of SYG-ICE sheet was destroyed and incorporated in new jam.

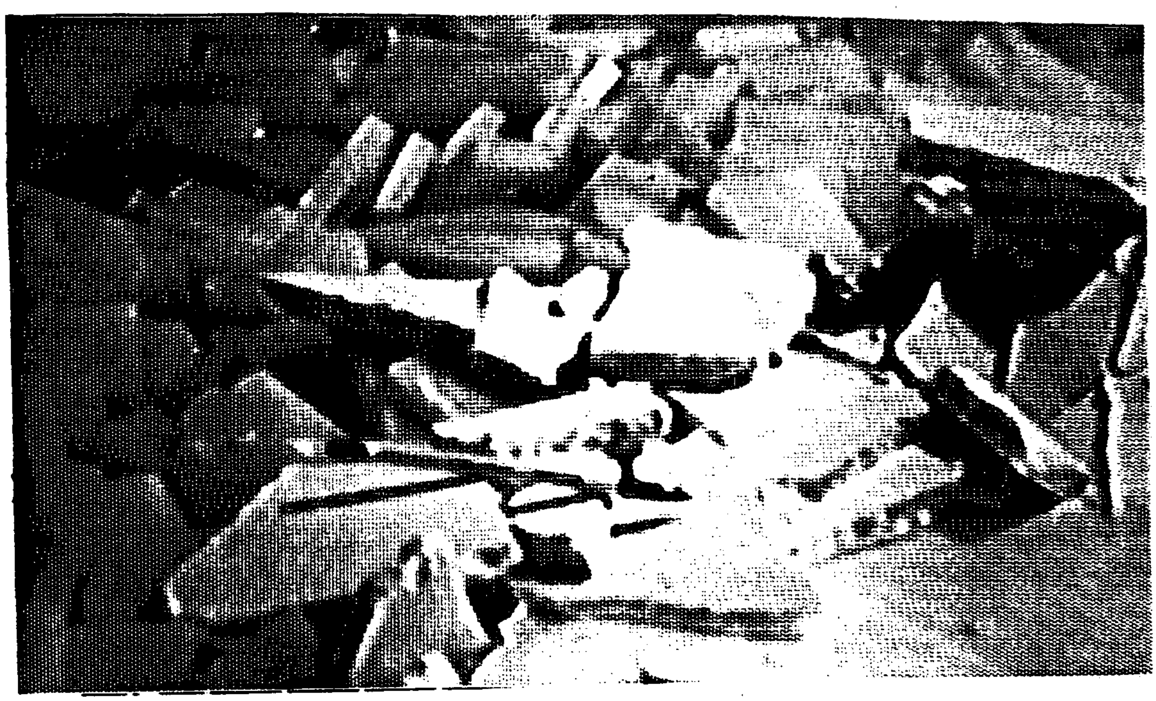

Fig. 2. Top view of ice jam held by SYG-ICE sheet. Note SYG-ICE fragment sizes similar to natural ice floes, relative to thickness.

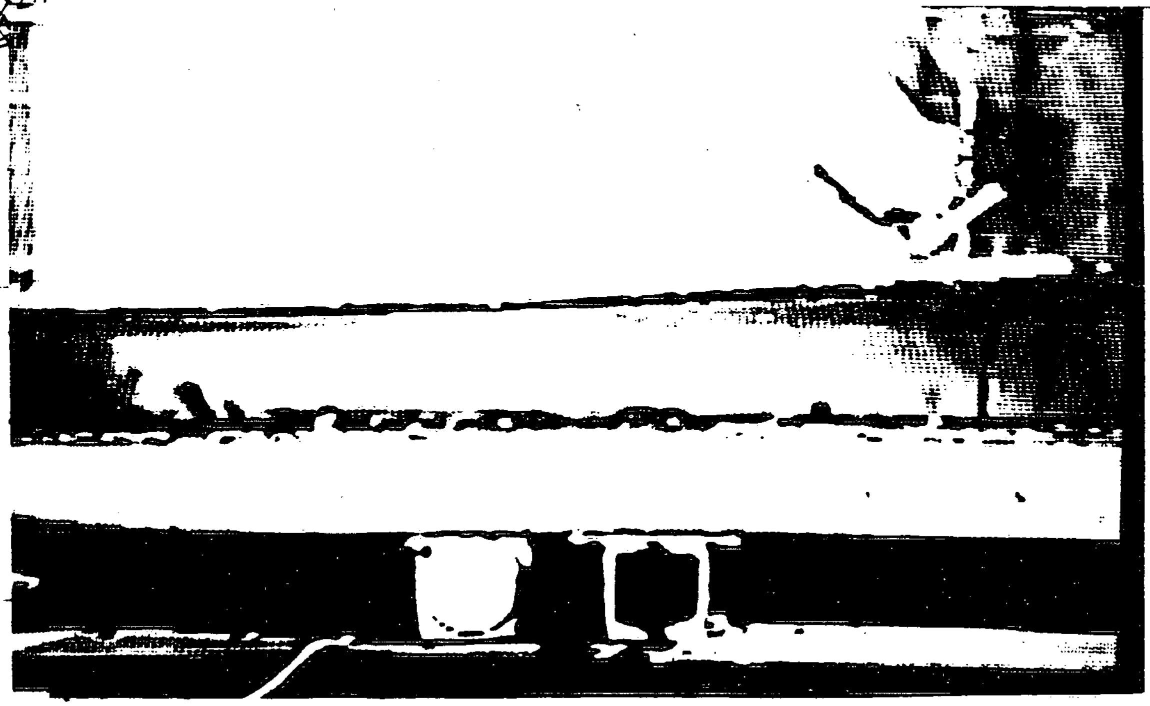

Fig. 3. Deformation of SYG-ICE sheet by an advancing wave.

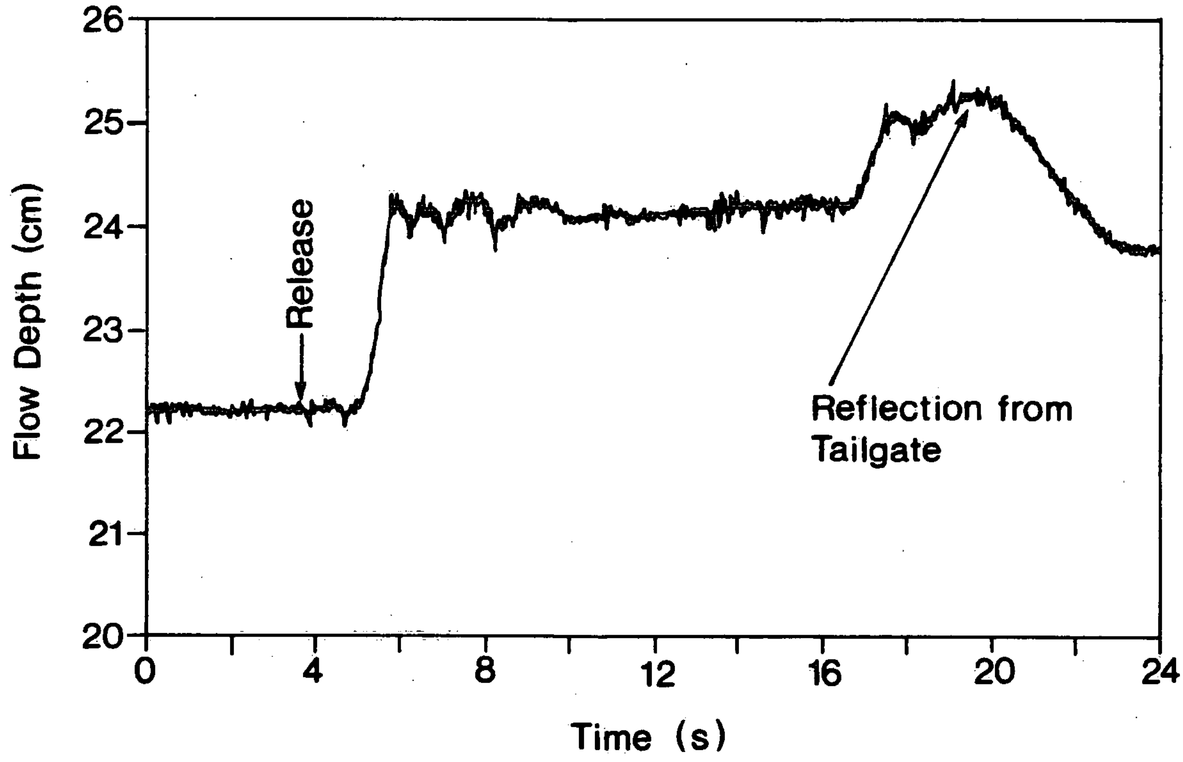

Fig. 4. Passage of surge as recorded at a site slightly downstream of "ice" edge. Test of August 17, 1987.