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Williams, G. M.

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PHYSICAL PROPERTIES OF FROZEN WOOD PULP

by

G. M. Williams

Report of tests on frozen wood pulp carried out in Montreal for the Montreal Engineering Company Limited during the summer of 1943 as part of an investigation on the properties of ice, under the direction of the National Research Council of Canada. At the time of this work, Professor Williams was on the staff of the College of Engineering, University of Saskatchewan.

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PREFACE

The possibility of major oil and gas developments in Northern Canada, particularly in offshore areas, has brought about an increased interest in the behaviour and properties of ice. This interest is not confined to the forces that ice covers might exert on structures, although that is a major problem. Ice covers can also be used as surfaces for roads and airstrips, and consideration is being given to their use as platforms for drilling operations.

In 1943 the National Research Council of Canada undertook, with the assistance of several university and other groups, a major investigation of the properties of natural and reinforced ice. At the conclusion of the war the information obtained in this study was assembled in the Council's files. Some of it is relevant to current interests and needs, and it has been decided to make it available for limited distribution in the Internal Report Series of the Division of Building Research.

The present report gives the results of a study conducted by Professor G.M. Williams, who, in 1943, was a member of the College of Engineering, University of Saskatchewan, on the strength and deformation behaviour of frozen wood pulp. This work was done in a cold storage plant in Montreal as part of the activity under the direction of the Montreal Engineering Company. It is presented in the same form as it was in 1943, without revision.

Many individuals participated in the field and laboratory research associated with this wartime activity. The Division of Building Research is privileged to be able to make the results of their efforts available for application to present-day problems of national concern.

Ottawa,
July, 1972

N. B. Hutcheon
Director.

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by

G. M. Williams

1. PURPOSE OF INVESTIGATION

This investigation was undertaken to establish the physical properties of frozen wood pulps of varying fibre content in connection with their possible use as a structural material. The work was done during June, July and August 1943 in Room 71 of Harbour Cold Storage, Montreal for the National Research Council, Ottawa, with the cooperation and assistance of the Montreal Engineering Company Limited, Montreal.

2. QUARTERS AND EQUIPMENT

Freezing, storage and testing of test specimens was done in Room 71, which was equipped with sufficient refrigeration to maintain a temperature of 0° F. Since tests were to be made at both 0° F and 15° F a Ten-Test partition was built, dividing the large room into two rooms having dimensions of approximately 28 by 90 ft and 38 by 90 ft, the former bounded by three exterior brick walls being held at 0° F and the larger one at 15°. Temporary partitions in an adjacent non-refrigerated hallway facing the elevators furnished a work and storage room and office space. Temperatures in different parts of the two rooms varied slightly depending upon nearness to the dividing partition, outside walls and doors, but thermometers in the centres of the two rooms held steadily between the limits of 0° to 2° F and 14 to 16° F. Throughout the report the test temperatures are referred to as 0° and 15° F.

The colder room was generally used for the freezing of test specimens and for conducting sustained loading tests at that temperature. The 15° F room contained large work tables on which specimens were prepared for test, the 60, 000-lb Riehle testing machine which was used for all quick tests, and machines for sustained loading tests. All quick tests were made in the 15° room but specimens to be tested at 0° were stored at that temperature until placed in the machine.

For the purpose of shaping test specimens a supply of wood scrapers, carpenter's wood planes, miter boxes and saws were provided. Specimens requiring plane and parallel bearing surfaces were "capped" with thin layers of pulp in much the same manner that concrete test cylinders are prepared for test.

Metal wash tubs and steel drums together with a platform scale were available for preparing and storing pulp mixtures. Determination of pulp content required a laboratory balance sensitive to 0.1 g, an electric hotplate oven and metal pans.

Measurements of test specimens and adjustment of testing equipment involved the use of steel scales graduated to 1/100 in. Deformation measurements in sustained loading tests were made with a Goodell-Pratt inside micrometer gauge with extension rods for measurements up to $12\frac{1}{2}$ in., reading to 1/1000 in. with an accuracy of about plus or minus 0.001 in.

3. GENERAL PROGRESS

Owing to delays in delivery of necessary testing equipment the work did not get underway until 21 June when the first specimens were frozen. In the meantime, the 60,000-lb Riehle two-screw testing machine borrowed from McGill University, which had been set up on a level wooden platform in the 15°F room, was available for use and many flexure and compression tests were made as specimens became available. Plastic flow or sustained loading tests were started 21 July when a sufficient supply of cast-iron loading weights was finally available. From that date until the close on 2 September the 35 dead-weight testing machines were in constant use to determine plastic flow rates of tension, compression, flexure and bond specimens. The test program could be planned in advance only in a very general way subject to constant change and modification as test data became available. Had the long delay in getting the work underway been foreseen, another 12 or 15 testing machines of the dead weight type might have furnished a more complete story in certain respects, notably in flexure and shear, but it is believed that the more important physical characteristics have been indicated as to general trend. Holding of the refrigerated space through the month of September permitted deformation readings of a number of the plastic flow specimens to be continued for another 35 days, which resulted in the definite confirmation of certain trends which had been indicated up to 1 September.

The staff of assistants consisted of two engineering students from Ecole Polytechnique, Montreal, and three high school graduates. While they lacked experience and required constant supervision, they soon became expert at work which required repetition and practically no test results had to be discarded because of errors or neglect in conducting the various tests. However, had an experienced engineer been available to supervise tests after procedure became routine, some other angles which were neglected might have been followed up.

4. GENERAL PROGRAM

Tests by others had shown that physical characteristics of frozen water are influenced by rate or temperature of freezing, conditioning temperature prior to test, and direction of applied load with respect to the optic axis or to the freezing surface. Another important variable, not found in most structural materials, is the tendency to deform or flow under constant load which is only a small fraction of that required to cause failure when quickly applied. In addition to these variables there was a possibility that the test program might have to be multiplied by the number of pulp mixtures or concentrations which it might seem advisable to include. The first work was designed to establish the relation, in quick tests, between pulp contents, temperature or rate of freezing, and temperature of test.

Fortunately, these preliminary quick tests indicated that pulp contents and temperature of freezing were not variables insofar as flexural and compressive strengths were concerned, and that these strengths were influenced mainly by temperature of test. Quick tests made in the power testing machine included flexure of plain and reinforced beams, compression of cubes and cylinders, tension, shear, shear of welded joints and bond of wood and steel reinforcement. As such quick tests may give little or no indication of the structural value of a material which is plastic these tests were duplicated on other specimens by the application of sustained loads, and noting the change in deformation with time. In general, all tests were made at the two temperatures of 15 and 0° F.

5. PULP AND ITS PREPARATION

All tests were made on water mixtures of ground wood lap. Ground wood lap is manufactured by disintegrating wood by pressing it against the face of a stone grinding wheel in the presence of a stream of water which serves to prevent burning of the wood fibre, and to carry away the finely divided material. The resultant product, with a fibre content of 1 or 2 per cent is pumped and formed into thin sheets, in much the same manner as paper is made, with water reduced to about 50 per cent, and which may later be reduced in storage to an average of about 40 per cent by further evaporation. Addition of more water plus a small amount of stirring or mixing such as would be supplied by a pulp beater or concrete mixer will result in a homogeneous suspension of wood fibre of any desired pulp content. The addition of a small amount of water, together with stirring, changes the material from the paper form to that of a heavy gummy substance having considerable adhesiveness in the mass but easily shredded with little tendency to adhere unless pressed or forced together. As water is increased and pulp content approaches 10 per cent the mixture can be trowelled and tamped into a homogeneous mass with little effort. At about 6 per cent it is quite plastic and semi-fluid and behaves much like a good working bricklayer's mortar, flowing into and filling a form with little tamping. A fibre content of 4 per cent or less appears watery with a tendency for the fibre to settle out. The watery appearance of the 4 per cent composition in contrast with the dry non-plastic condition of 12 and 14 per cent pulp is apparent in Photo No. 26.

Basing selection of pulp content on tendency to remain in suspension, at one extreme, and to result in a mixture which would retain some plasticity and flowing property with a reasonable application of energy, at the other, it seemed that a pulp content somewhere between 4 and 8 per cent would be desirable. Within these limits the consistencies are much the same as those of portland cement concretes used in structural work for which machinery has been developed for mixing, transporting and placing. Most tests were made on one or all of the 4, 6 and 8 per cent compositions but others were included as shown in the tables of test results.

Early tests were made on 4 per cent pulp prepared in the beater of the Pulp and Paper Institute at McGill University but, since this was the heaviest that could be prepared there, most of the needed pulp was worked up at the laboratory in small batches of several hundred pounds as required.

Large quantities could have been more efficiently prepared in a power concrete mixer but hand preparation of smaller quantities at intervals reduced the possibility of the stock souring, and furnished a means of warming up after exposure to low temperatures in the test rooms. Weighed quantities of the moist lap were torn up and soaked with the required amount of water for a period in metal wash tubs after which pieces of 4- by 4-in. timber with handles attached to one end were applied, in much the same manner as concrete tampers, except that the timber was given a rotary motion at the bottom of the stroke. The resultant laboratory product, having a concentration of 10 to 12 per cent pulp which could later be reduced as needed, appeared somewhat lumpier and less uniform than that turned out by the beater at the Institute. Slightly higher flexural strengths were obtained with the Institute pulp than resulted for laboratory pulp in later tests.

Although pulp beaters used in the mills are not required to turn out concentrations of 4 per cent or greater, there would seem to be no mechanical difficulty involved in adding one or more additional power units to mill beaters and thereby increasing fibre content to 6 or 7 per cent.

6. PREPARATION OF TEST SPECIMENS

Test specimens for flexure, compression and plastic flow were generally molded and frozen in wooden beam forms made of $1\frac{3}{4}$-in. dressed lumber. Most of these beams, cast in one or two layers, were 4 in. wide, 4 in. deep and 43 in. long. A few were 4 by 8 in. by 85 in. cast in two layers. With form sides, bottoms and ends of such thickness, heat loss occurred mainly through the upper exposed face of the beams. After flexure tests in which the small beams were loaded at the 1/3 points* with a 40-in. span, cubes cut from near the ends were used for compression tests. Compression plastic flow specimens were cut from untested beams.

Tension test specimens were cast in wooden forms previously used in the University of Saskatchewan tests. These test specimens were 2 in. deep and 24 in. in over-all length with the reduced centre portions having widths of 3 and 4 in. respectively. As tested the load was applied parallel to the exposed frozen surface. For the purpose of measuring the tensile strength of welding planes at the junction of successive fillings a number of tension specimens were cast on-end after enclosing the open side of the forms and removing one of the end pieces.

Specimens for testing the bond strength of reinforcing rods, as well as cylindrical compression test pieces, were cast in watertight paper containers of 1 quart capacity having a diameter of 3.3 in. and height of 8 in.

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* Also referred to as 4-point bending. This type of loading produces a constant bending moment over the central portion of the beam.

Shear test specimens to measure the strength of welded joints were made by joining the vertical faces of three cubes cut from beams, the centre cube projecting about 1 in. above the two outer ones, with the bases of the two outer cubes welded to a piece of 4- by 4-in. timber to prevent lateral spreading or tilting when load was applied downward on the upper horizontal face of the centre cube.

To determine the shearing strength of homogeneous frozen pulp free from ice seams or welds, specimens of similar shape were cut from 4- by 8-in. beams.

Tension tests of wood reinforcement were made on wood samples whose ends were embedded in pulp in the grip portions of the tension forms with the centre 6 in. of the wood strip dammed off to prevent encasement.

Specimens were loaded in two directions to measure plastic flow in compression. For loading parallel to the frozen face a specimen of sufficient length was cut from a beam and the 4- by 4-in. ends made plane and parallel. Preparation of similar specimens to be loaded perpendicular to the frozen face involved cutting three cubes which were placed one above the other with welds at the two junctions and making the bearing faces plane and parallel.

Specimens were frozen at 15 and 0° F with most of the freezing done at the lower temperature. About 20 hours were required in still air to freeze a 2-in. beam layer or the 2-in. tension specimens. Beams poured in a single 4-in. layer were not completely frozen at the end of 24 hours. Casting in 2-in. layers resulted in less warping and distortion but caused the formation of an ice plane of varying thickness between the layers. This pure ice seam is always formed at the top of the first layer due to pure water being forced out through the frozen surface. No attempt was made in our tests to roughen or remove this ice layer prior to adding fresh pulp. The ice seam formed between successive layers is shown in Photo No. 13, welded beams, and in Photo. No. 24.

7. QUICK TESTS

The term "quick test" refers to tests made in the Riehle power testing machine. Generally the test was completed and the specimen destroyed within a period of 5 to 15 minutes. It was found that the application of strain at the rate of 1 in. per minute was satisfactory in flexure but entirely too fast to permit proper control of the poise of the weighing beam in compression tests. Since a plastic material may eventually fail under a load which may be a small fraction of that attained in quick tests it was decided to adopt as standard speed the lowest available, which was 0.1 in. per minute. In a few cases a speed of 1.0 in. per minute was used as indicated in the strength tabulations.

As individual test results and their variation may be of more importance than average values in the case of a new material, results of all separate tests are given and no test results have been omitted because of wide variation from general averages.

(a) Flexure

All beams were tested with 4-point loading with roller bearings at supports and at points of application of load. All failures were tension failures generally preceded by considerable deflection caused by plastic flow in compression. There were no indications of failure due to diagonal tension, shear or bearing. Ice seams at the neutral plane of specimens frozen in two layers did not appear to be a source of weakness. All computed values for failure strength are based upon elastic theory. Beams containing reinforcement are computed in the same manner as a plain beam of the same cross-section. Photo No. 12 illustrates the equipment used.

Tables 1 and 2 show results of early tests to determine effect of freezing temperature, temperature of test and pulp content.

These test results eliminated several factors as important variables and considerably narrowed the test program. Rate of freezing appeared to be of little importance and a 100 per cent increase in pulp content from 4 to 8 per cent had no appreciable effect on flexural quick strength. Later, tests of specimens frozen quickly in 3/8-in. layers in the wind tunnel indicated that the same relation held for tension test specimens.

In Table 3 are grouped other flexural tests on 4- by 4- by 43-in. beams for pulp contents ranging from 1 to 14 per cent.

In Table 3, A = 15° and B= 0° F. In each case the first letter refers to the temperature of freezing and the second refers to the test temperature.

Although the average flexural strengths for the different pulp concentrations do not differ greatly, there appears to be a slight increase with increase of pulp content. This trend might be even more evident had all pulp been worked up in the same manner. The slightly higher values obtained for early specimens of 4 per cent pulp are probably due to the more complete beating and separation of the fibres of the lot prepared at the Canadian Pulp Institute.

In Table 4 are shown results of flexural tests of plain beams tested in the usual manner with frozen face up compared with similar test specimens tested with the frozen face below on the tension side, or rotated through 90° so that the frozen face was at the side.

A few large beams 4 by 8 in. in cross-section and 85 in. long were cast in 2 layers and tested with 4-point loading and span of 80 in. Although the number of large beams tested is rather small the results seem to indicate flexural strengths somewhat lower than expected. This trend of lower strength with increase in size is consistent with similar tests on other structural materials. A few large beams were made by welding together four of the smaller 4- by 4-in. beams. The compression faces were made up of two 4- by 4- by 43-in. with beams with a butt joint at mid-span while the lower tension face was composed of one 43-in. beam at the centre with half lengths welded to either end. Photo No. 13 illustrates this type of welded beam. The welded beams failed at a lower failure strength and the test results are in fair accord with tests of other welds, indicating that while welds are not as strong as homogeneous pulp they can develop a substantial percentage of the strength of the pulp body. Test results of large beams, homogeneous except for the ice plane at the junction of the 4- in. layers, are included in Table 5. In Table 6 are listed the tests on the built-up welded beams together with retests on the same beams after the fractures were re-welded.

(b) Compression

Compression tests were made on small samples, generally 4-in. cubes, of all materials tested in beam form. After the flexure tests four cubes were cut from broken portions near the end of the span. Two were tested with the load applied parallel to the frozen surface (along the axis of the beam as cast) and two with the load applied perpendicular to the frozen surface. As in the case of frozen water or ice, the compressive strength normal to the frozen surface was greater than that parallel.

	15° F		0° F	
River Ice	Parallel	Perpendicular	Parallel	Perpendicular
	560	905	415	840

These river ice specimens (see diagram no. 14) are the ones reported under plastic flow (compression) and had been subjected to sustained loading for a period of about two weeks. The "parallel" specimens had corrugated, bulging sides due to sustained loadings of 50 and 75 psi. It is not apparent why the ice at 15° F should test higher than that at 0° F. Rate of plastic flow of these same specimens was greater at 0° F than at 15° F, contrary to what would be expected.

In Table 7 are grouped all of the compression tests of pulp cubes as well as a few tests of river ice and tap water ice frozen in beam molds. Table 8 includes compression tests of frozen pulp cylinders cast and frozen in cardboard cartons. The cylinder test pieces were cast as a unit and were free of ice planes and seams. Temperatures of freezing, as well as tests, were 0° F and 15° F for the three pulp contents of 4, 6 and 8%. These test results verify the earlier conclusions that, under these conditions of test, strength is dependent mainly upon temperature of test. Table 9 comprises compression tests made on pulp prisms approximately 4 by 4 by 8 in. which had been used previously in determining the specific gravity and weight per cubic foot of frozen pulp. Top and bottom surfaces of all compression test pieces were cushioned with Beaver Board to equalize the load. Compressive strength in quick tests appears to be little affected by pulp content.

(c) <u>Tension Tests</u>

Tension test specimens were frozen in molds (previously described) and were tested in the power machine. As indicated in Photo No. 3 the specimens were too long to be suspended in the usual manner so that a wooden frame resting on the weighing table of the machine served as the fixed upper head. Most specimens, after the original test, were welded and re-tested once, and a few twice. Table 10 includes test results of specimens having a minimum cross-section of 6 sq in. Tests of specimens having an 8-sq-in. section are grouped in Table 11. All specimens fractured in the reduced sections well away from the grip ends. Results of tests of a few quick-freeze tension specimens frozen in thin layers in the wind tunnel are also included in Table 10.

Welds were made by coating a fractured surface with pulp of the same composition, squeezing the two ends together, and trimming off the junction after freezing.

Tension specimens with ice seams normal to the direction of applied load were made by standing the tension forms on end and pouring layers on successive days so that there would be two or three weld planes in the sections of minimum cross-sectional area. Since the upper surfaces would not remain plane during freezing the boundaries between layers consisted for the most part of thin layers of pure ice binding irregular and rough pulp masses. These surfaces were not scraped or roughened in any manner prior to placing the next layer. Although the results of tests reported in Table 12 are erratic most values are considerably in excess of values that have been reported for pure ice in tension.

The test results of Tables 10 and 11 show a definite increase in tensile strength with increase in pulp content in quick tests.

(d) Bond Tests

Bond test specimens were made by casting wood and metal rods vertically in cylindrical watertight cartons about 8 in. high. Tests were made by pushing out the rods at a speed of 0. 1 in. per minute. To prevent compression failure of wood above the specimen it was necessary to reduce the projecting height to less than 1 in. and the cylindrical test specimens had to be sliced into discs less than 1 in. thick in order that slippage of rod would result without compression failure in the wood. To prevent contact of the test bar with the lower bearing plate, the lower ends were "capped" with pulp after the end of the rod had been covered with a chunk of putty. After the pulp base was frozen the putty was dug out prior to test. Results of bond tests of wood contained in Table 13 are higher than those for steel listed in Table 14. As discussed later under beam tests wooden reinforcement showed no signs of bond failure but steel reinforcement in beams slipped even though the ends were bent into the shape of a standard reinforced concrete hook.

(e) Shear Strength of Frozen Pulp and of Welded Pulp

As described previously shear test specimens were built up by welding together 3 cubes with the bases of the two outer cubes welded to wooden blocks. Homogeneous pulp specimens, similar in shape, were also cut from the ends of 4- by 8-in. beams. While the two boundaries of each weld consist of pure ice the quantity of pulp in the mortar appears to influence strength of the joint in shear as indicated by the test results of Table 15 covering welded specimens. As would be expected the shearing strength of pulp without ice planes (Table 16) was considerably higher. The values of 600 to 800 psi are approximately one half of the quick compressive strength, a relation found for portland cement concretes.

(f) Tension Tests of Wood Reinforcement

The $\frac{1}{2}$-in. square white pine strips used as reinforcement in some beams were tested by embedding the ends in frozen pulp in the tension forms. The wood was clear select white pine, free from knots and fairly straight grained. As shown in Table 17, four pieces selected at random varied nearly 300 per cent in tensile strength. The chief defect of wood as tension reinforcement lies in the wide strength variation found for material which appears to be of uniform high quality. This method of gripping the ends of wood tension specimens overcomes one of the main difficulties met with in determining the tensile strength of wood. All four failures occurred well away from the embedded ends. Photo No. 18 shows this form of test specimen.

(g) Freezing Time for Pulp

Time required to freeze pulp under various conditions of air temperature and velocity, pulp content and thickness of layer was determined in a wind tunnel about 8 ft long and 2 ft square, inside dimensions. Blast was furnished by a 22-in. 8-bladed fan mounted on a heavy cast-iron base at one end of the tunnel. Air velocity over the freezing surface was controlled by varying the distance between the inlet end of the tunnel and the fan. Test slabs of 80 sq in. were built up in a horizontal position on the floor of the tunnel and air velocities were measured 1 in. above the freezing surface by means of a Pitot tube and a Friez air meter graduated to give a direct reading of air speed in feet per minute for any test temperature. Temperatures were measured by means of copper-constantan thermocouples embedded near the bottom of the freezing layer, using a Leeds and Northrup potentiometer for measuring voltage. This instrument was located in a room at ordinary air temperature and was connected to the thermocouples by means of a 150-ft lead-covered cable. Depth of test layer was controlled by the use of wooden strips whose depth was the exact thickness desired.

The freezing times reported are the length of time intervals during which the potentiometer registered 0, while the temperature of the pulp in contact with the thermocouple was at 32° F. The approximate time required at the beginning of each test for the pulp to drop to 32° F was also noted and recorded. Time required to drop to 32°, after placing, is dependent upon temperature of the fresh pulp and that of the frozen layer on which it is placed, as well as time required to place the layer and to get the air blast in operation.

The attempt to compute theoretical output per day is of doubtful value without detailed knowledge of the type of equipment and plant to be used. It is very unlikely that a plant of commercial size could operate at 100 per cent efficiency which would require placing of a new layer and exposure to the blast at the instant the freezing mass drops just under 32° F. The lost time in sequence of operations might be an appreciable percentage of the freezing times listed in Table 18 and shown graphically in Diagram No. 1, so that actual production might be considerably less than the theoretical capacity.

Based on the results of Table 18 the following estimates of production assume a plant operating efficiency of 80 per cent.

Air Speed	- 17.5 m.p.h.	4° F	3/8-in. layers	---	13 in./day
" "	- 12.5 m.p.h.	4° F	3/8-in. layers	---	10 in./day

Freezing times for the 14 per cent pulp were appreciably shorter than for the 6 per cent. The individual results for 6 per cent were also more variable. Some of the variation may be due to the relatively thin layers and slight variation in the position of the thermocouple with respect to the vertical boundaries of the layer as well as the diameters of the thermocouple wires. In screeding off and troweling the relatively wet 6 per cent pulp a variation of 1/16 in. in thickness would result in a variation of 16 per cent in thickness. The procedure involved in these tests was standardized and the electrical apparatus functioned perfectly so that the freezing times reported are probably a fair measure of the variable factors involved.

(h) Tests of Reinforced Beams

Quick tests, as well as plastic flow tests, were made on a few beams reinforced with wood and steel. Tests are insufficient in number to permit definite conclusions except that reinforcement is generally effective in somewhat increasing the computed failure strength and permits a much greater deflection prior to failure. Wood appears to be more effective than steel although deformed bars or rods with lugs welded on might overcome the tendency toward early bond failure which is probably responsible for the relatively lower strength of this type of reinforcement. Since carrying capacity of a beam is probably controlled mainly by plastic flow on the compression side (discussed later under Plastic Flow of Beams) which requires that flexural stress be kept low, bond strength of the reinforcement may not be important under practical working conditions. The poor showing of steel with standard concrete specification hooks at the ends was unexpected.

Quick test results of reinforced beams in flexure are listed in Table 19. Variation in tensile strength of the $\frac{1}{2}$-in. square wooden reinforcing, previously noted, may account for the results obtained with 4 per cent pulp. In contrasting results obtained for wood and steel reinforcement in beams it should be noted that the cross-sectional area of reinforcement in wood-reinforced beams was 5 to 10 times the area of steel in those reinforced with steel and that surface area per inch of length to resist bond was $2\frac{1}{2}$ to 4 times as great for wood.

These tests show no advantage for hooked ends over plain, straight ends for steel.

Interesting results, but of little practical value, were observed in a retest of some of the beams reinforced with $\frac{1}{4}$-in. diameter steel rods with hooked ends. In the original tests, at a speed of 0.1 in. per minute, failures occurred with loads of 1300 to 1650 lb and computed flexural stress values of 900 to 1100 psi. These beams were later loaded at a rate of 1.0 in. per minute during which time the loads carried were greater than during the original test with a deflection as great as that shown in Photo No. 16. The wide crack was apparent up to within $\frac{1}{2}$ in. of the upper face of the beam; apparently the pulp beam and the wooden beam through which loads were applied at one-third points along the span were functioning together as an inverted "A" truss with the two pulp halves of the pulp beam subjected mainly to tension, carried by the steel, and not to flexure as at the start of the test. Slippage of steel and straightening out of one of the hooks, first noted in the original test at low speed, is shown in Photo No. 17.

(i) Unit Weights and Specific Gravity of Frozen Pulp

Since frozen specimens are not uniform in shape or dimensions, computations of weight per cubic foot based upon measured dimensions may be appreciably in error and determinations of unit weights of several samples cut from the same large specimen may differ considerably.

The values listed in Table 20 are based upon volume displacement of a liquid (kerosene). Samples were approximately 4 by 4 by 8 in. homogeneous and free of ice seams, and weighed about 4 lb each. Compressive strengths of these specimens are listed in Table 9.

(j) Modulus of Elasticity of Frozen Pulp

As pointed out in the second section, "Plastic Flow," there is no constant relation between stress and strain for frozen water or pulp. Even though applied loads are a small fraction of the quick ultimate strength, deformation continues to increase with time as the constant load is maintained. For elastic materials, for which a constant ratio between stress and strain is found to be independent of time so long as the stress is below the elastic limit, the relation

$$\text{"E"} = \frac{\text{unit stress}}{\text{unit strain}}$$

holds, but since strain varies with time, for pulp the time variable must appear and for pulp this equation might read:

$$\text{"E"} = \frac{\text{unit stress}}{\text{unit strain x } t^{x}} \quad .$$

Since the denominator is a variable, "E" cannot be a constant. Computation of "E" for pulp based upon the results of quick tests, in any form, is therefore meaningless and of no value for structural purposes where load is a constant for an indefinite period of time.

8. SUSTAINED LOADING TESTS AND PLASTIC FLOW

(a) General

Plastic flow, or continued deformation without increase in load, was observed in several types of quick tests in the power testing machine. This effect was evidenced by the tendency of the weighing beam to drop while strain was steadily applied to the specimen. After being down for a period of time the beam would rise and, to maintain balance, the poise would be moved out for a short period after which the beam would again drop. This action occurred in compression at a speed of 0.1 in. per minute and in flexure tests at speeds of 0.1 and 1.0 in. per minute. In compression tests of cubes this alternate dropping and rising of the weighing beam might have continued indefinitely or until the specimen was reduced to a fraction of its original height. There is no definite point of failure of a compression specimen. As slow loading is continued lateral dimensions are increased so that after the specimen is reduced to a fraction of its original height the unit load on the enlarged area is considerably greater than at any earlier period of the test. In a sense the material has become stronger than it was at the start of the test, but deformation has been so great that it has lost all value as a structural material. In the quick tests the first decided drop of the beam was preceded by a reduced rate of movement of the poise so that there was no difficulty in detecting "maximum load" except for the high pulp contents for which drop of beam was less pronounced.

The increase in strength accompanying excessive deformation is shown in Photo No. 21 which shows a 4-in. cube before and after crushing. The specimen at the right originally had a cross-section of 13.85 sq in. and loaded in the usual manner at the rate of 0.1 in. per minute "failed" at 11,000 lb or 795 psi. The rate of loading was then increased to 1.0 in. per minute and, as height decreased, lateral dimensions increased so that the pulp spread beyond the limits of the 6- by 6-in. bearing plates. When the machine was stopped the specimen was carrying 44,570 lb, a unit stress of 1255 psi on the new area of 36 sq in. Time required to reduce the specimen to the height shown in Photo No. 21, after initial failure, was a little over 2 minutes.

Beams, in flexure tests, performed in much the same manner as cubes in compression. Plain beams would deflect as much as 3/8 to $\frac{1}{2}$ in. with tension cracks opening up within the middle third of the length before failure. Reinforced beams, especially those reinforced with wood, would deflect as much as $1\frac{1}{2}$ in., requiring 12 to 15 minutes of operation of the machine at 0.1 in. per minute. A large part of the total load would be registered within the first few minutes, with additional increments of 20 to 50 lb with long time intervals between, during which the weighing beam would drop. Photo No. 12 illustrates the deflection of a wood reinforced beam during test when the amount was about 1 in.

This plastic flow under sustained load which may be a small fraction of the "quick test" strength indicates the relative unimportance of all of the foregoing quick test results. Quick tests fail to give any reliable indication of safe loads which may be used in practice and their use in an attempt to measure structural behaviour of pulp will lead to unsafe design if factors of safety similar to those employed with elastic structural materials are selected.

Diagram No. 2 shows graphically the deformation with time of a specimen loaded in compression with a sustained load of 400 psi. The extremely rapid rate of the first few hours tapers off at about 40 hours to a lower rate of 0.29 in. per inch per year which is at a rate of 29 per cent per year. This deformation time relation is shown here as a typical example of the reduction in rate of deformation with time when load is a constant. The applied unit load was about 40 per cent of the ultimate "quick test" value and the later 29 per cent rate per year did not decrease with time.

In Diagram No. 3 are shown results of tests in which a prism was loaded and unloaded a large number of times. A load of 200 psi was applied for 5 minutes, the load removed, and the specimen allowed to rest for 2 minutes. This loading was applied a total of 5 times, deformation readings being taken just before release of load and again before a new application. After a 10-minute rest the sequence was repeated for 400 psi then with 600 psi, followed by a repetition of the 200 psi loading. After 24 hours without alteration of position of the specimen in the testing machine a series of 200 lb then 400 lb and finally 200 psi loadings were repeated. A week later the same specimen was subjected to further loadings of 200, 400 and 200 psi. The decrease in total deformation which also represents a decrease in rate of deformation is apparent from the graph which also shows the absolute height of the specimen, originally about 7.2 in., during the test. The appearance of the shortened test piece together with surface deformations or bulges is contrasted with an identical untested specimen in Photo No. 22.

A beam was tested in somewhat the same manner by loading and unloading it with rest intervals between and measuring deflection. The results are not extensive enough to justify definite conclusions but it is apparent that the trend of decreased deformations with repeated loadings found for the prism loaded in compression is apparent here also. The deflection and recovery after loading is shown in Diagram No. 4.

These tests as well as all of the beam and compression specimens, described later, which were subjected to steady loading indicate that rate of deformation decreases during the first 24 to 40 hours even though the load is sufficient to result in failure in a comparatively short period of time. Smaller loadings will result in a decreased rate of deformation not only during the initial period but throughout the test so that the rate approaches or actually becomes zero. None of the test data obtained throughout the work indicated a change in physical properties comparable to the work hardening of low carbon steel brought about by application of stress well beyond the elastic limit after which the yield point becomes higher with a loss of ductility or elongation.

In the sustained loading tests deflection or deformation readings were taken for periods ranging from a few days to two months. Since it is difficult to compare test data or draw conclusions from tabulated figures the results of bond tests of reinforcing bars, plastic flow in tension and deflections of beams subjected to sustained loadings are shown in diagram form. Results of plastic flow of compression test specimens carrying sustained loadings are shown for the most part in terms of rate of deformation per year obtained from diagrams showing relation between deformation and time.

(b) Slip of Reinforcing Bars under Sustained Loads

Sustained bond tests are shown in Diagram No. 5. All tests were made with 6 per cent pulp. Only two specimens containing steel reinforcement were subjected to sustained loading. One which showed a small rate of slip at 50 psi apparently failed soon after the load was increased to 75 psi although this was not verified by inspection at the close of the test. The other specimen showed slight slip at 25 psi for 13 days, showed a greater rate when the load was increased to 50 psi.

Wooden bars of larch 3/4 in. square and surfaced on two sides showed slight progressive slip for 50 psi at both 15° and 0° F.

One test of a $\frac{1}{2}$-in. round birch dowel bar showed movement at a slow rate for 75 psi at 15° F.

These tests are too few in number to permit of definite conclusions being drawn but they appear to indicate that a bond stress of 50 psi at 15° F might be safe for wood.

(c) Plastic Flow in Tension

Large tension specimens similar to those used in the quick tests were held in wooden grips, and were loaded by means of a beam and cast-iron weights as illustrated in Photo No. 4. Since only four test pieces were involved it is again impossible to draw definite conclusions but it appears that there is little plastic flow for unit loads which may be as much as one third of the quick ultimate strength. For some unknown reason one specimen loaded to 100 psi persisted in shortening instead of lengthening as would be expected (See Diagram No. 6).

These results seem to justify the statement that plastic flow or deflection in flexure for small sustained loads is due to plastic flow on the compression side of the beam.

(d) Plastic Flow in Flexure

Diagram No. 7 shows graphically the deflection-time relations for 4- by 4- by 43-in. beams with 40-in. span loaded at the third points. At each temperature one beam was tested with the frozen face up and one with the frozen face on a side. After application of load sufficient to result in a fibre stress of 95 psi for a few days at 15° F the load was increased to 165 psi. Deflections then increased for 3 days after which there was no increase for a period of 10 days. Load on one specimen was then increased to 305 psi and deflection increased rapidly at a uniform rate which would have resulted in fracture had the test been continued. Two beams at 0° F were held at 100 psi with no progressive deflection after the 2nd day.

Test results in Diagram 8 cover too short a period of time to be conclusive but appear to indicate no progressive deflection for stresses of 100 psi.

Deflections of 4 per cent and 6 per cent beams at 0° F over a period of 1800 hr are shown in Diagram No. 9. After applying initial stresses of 100 psi followed for a short period by 150 psi load was increased to result in stresses of 200 psi for the remainder of the test period. While the curve flattens slightly toward the end of the period, the indications are that failure would have occurred had the test been prolonged. Beams are at a disadvantage as compared with compression test pieces since there is no increase in lateral dimensions which might tend to reduce flexural stresses. It will be noted that load was removed at 550 hr with some recovery, but reapplication of the load caused the same deflection at the end of another day which would have resulted had there been no removal of load.

Plastic flow of two 4- by 8-in. beams is illustrated in Diagrams Nos. 10 and 11. Continuation of the loading of 200 psi would probably have resulted in failure. Centre deflections in the span of 80 in. had become 0.59 in. and 0.68 in. when the tests were discontinued. Release of load for 24 hours resulted in a recovery of about 0.1 in. at 424 hours but 24 hours after loads were re-applied deflection was about the same as it would have been had loading been continuous.

Diagram No. 12 shows the time-deflection relations for beams reinforced with wood during a 1200-hr test period. At the end of this period the beam having a $\frac{1}{2}$-in. square tension rod was deflecting at a much lower rate than the beams of Diagram 9 for the same stress of

200 psi. The beam with 3/4-in. square tension and compression reinforcement had almost reached equilibrium. These tests do not indicate whether tension or compression reinforcement is most effective. The beam with the $\frac{1}{2}$-in. tension bar indicates that some reduction in deflection is due to reinforcement on the tension side. There was no indication of bond failure in any beams reinforced with wood in quick flexure or sustained loading tests.

While these flexure tests are limited both in extent and duration they seem to indicate that plain beams will deflect indefinitely if stressed to 200 psi.

(e) Plastic Flow in Compression

Results of sustained loading tests in compression are summarized in Tables 21 and 22. In Table 21 are included all compression specimens comprising pulps of 4, 6 and 8 per cent concentrations, tested at temperatures of 0 and 15° F, loads applied parallel and perpendicular to the frozen surface, and including loads ranging from 100 to 400 psi. Reported results of tests for the foregoing variables are plastic flow in per cent per year, or percentage deformation in inches per inch per year.

Specimens were prepared with plane parallel ends and mounted on steel plates in the loading frames (see Diagram No. 15) where load was applied through a loading beam with a 10 to 1 ratio. Cast-iron scale weights of 10, 5, 2 and 1 lb combinations were used to make up the required loads. Readings of deformation were taken between the upper and lower bearing plates by means of an inside micrometer of adjustable length which was read to the nearest 0.001 in. Readings were taken opposite the faces of test prism which were under the loading beam.

To attain unit loads of 300 and 400 psi it was necessary to reduce the lateral dimensions of the test pieces to 2 in. by 2 in. which in turn led to bending stresses of considerable magnitude owing to unavoidable eccentricity which resulted in the attempt to centre the knife edge of the loading beam above the centre of the test piece of small area. Eccentricity of loading and its amount was apparent in the daily readings of deformation and the reported rates of plastic flow are larger than would have been found for specimens of larger cross-section. Only one of the larger test specimens loaded to 100 and 200 psi showed evidence of appreciable eccentric loading and the test was continued without readjustment in order to observe the effect of such a loading without the accompanying buckling of the specimen which was always noted for the smaller test pieces. This specimen is 24-1-X as listed in Tables 21 and 22.

Values reported in Tables 21 and 22 were obtained by plotting the time-deformation values to a large scale and determining the slope of a line which averaged the plotted points. Diagram No. 2 which shows the deformation with time of specimen 28-F illustrates the method. It was apparent soon after sustained loading tests of compression specimens were underway that a constant rate of flow was attained after the first few days only by those specimens which were on their way to early destruction due to high unit stresses or eccentric loading or a combination of these two factors. Specimens carrying unit loads up to 200 psi and which were fairly centrally loaded without exception showed decreasing rates of plastic flow with time instead of constant rates, which other tests had indicated should be expected. The necessity for keeping specimens under test for an indefinitely long period of time reduced the number of test pieces which could be loaded, although 24 dead-weight loading machines were available. Specimens kept under test until the equipment was dismantled, and first listed in the large group in Table 21, are reported again in Table 22 with rates of plastic flow computed for two later periods beyond the first 200 hr reported in Table 21. For specimens loaded to 100 and 200 psi the flow rates for the first 200 hr ranged from 1. 40 to 5. 46 per cent. These values had decreased and ranged from 0. 76 per cent to 0 per cent toward the close of the work. Specimen 24-1-X in preliminary tests had shown the same rate as 22-1-X. Eccentric loading, apparent from the start in the final tests, resulted in an early flow rate of 11. 45 per cent per year but this was reduced to 3. 40 per cent for the last 800 hr. Specimen 22-1-X in final tests showed a flow of 0. 55 per cent. Specimen 26-L, a 2- by 2- by 6-in. specimen loaded to 300 psi was approaching a rate of about 1. 00 per cent per year when the test was discontinued.

Diagram No. 13 shows graphically the time-deformation relation for several specimens which were kept under test to the end of the work. The four specimens of Series 22 are directly comparable and indicate the effect of temperature and direction of loading on rate of flow.

The Series 53 specimens were each reinforced with a $\frac{1}{2}$-in. square wooden rod placed in the centre of the specimen and in the direction of the applied load. Their initial rates were $3\frac{1}{2}$ per cent per year and for the last 800 hr their rates were 0. 34 and 0. 33 per cent per year.

Rates of flow for river ice at 0° and 15° and for loads parallel and perpendicular to the freezing surface are included in Table 21. Note that initial loads were 50 and final loads 75 psi. As would be expected, greatest flow occurred for loads applied parallel to the freezing surface (perpendicular to the optic axis), but the results seem inconsistent in that greatest rates of flow occurred at 0° F, for both directions of loading. This contradiction of results is not due to a mix-up of specimens or interchange of report sheets. Both specimens loaded parallel to the freezing surface were on their way to failure when the tests were discontinued and the sides of the specimens were wrinkled or corrugated as is apparent in Photo No. 22 for the pulp test specimen 51-1, referred to at the beginning of the discussion of plastic flow.

These tests would seem to indicate that rate of plastic flow for sustained loads in compression will be less than 1 per cent per year for loads as high as 200 psi. Total deformation may range from 0.2 per cent up to 0.6 per cent or more per year being less at 0° F than at 15° F and occurring mostly at early ages. Reduction of unit loads to 100 psi will reduce rate of flow to 0.5 per cent per year or less with a smaller total deformation than for the 200-lb load.

9. GENERAL CONCLUSIONS

It appears that the structural use of frozen pulp and the selection of allowable working stresses in order that rate of plastic flow and total deformation will be small should be based upon sustained loading tests in flexure and in compression. While quick tests may indicate trends which are established by sustained loading they are of little value and their use may actually lead to unsafe designs. Quick tests may also be misleading if applied to the selection of proportions of pulp which may appear best suited for use structurally. While tensile and flexural strengths are greater for the higher pulp contents in quick tests this relation does not hold for compressive strength. Sustained loadings in compression likewise indicate that rate of plastic flow appears to be independent of pulp content so that selection so far as structural values are concerned, should be based upon combined cost of pulp and cost of forming structural units which will in turn be influenced by methods selected for production of frozen material. Another factor of importance is the efficiency of the welding material used in joining together the structural masses. Since the weld material will probably not exceed a 6 per cent concentration it would seem that the use of a higher concentration for the structural units would be influenced by factors beyond the scope of the physical properties covered in this report. Each weld is bounded by two ice planes whose lower physical values, as compared to those of homogeneous pulp, should set the standards for use in structural design.

TABLE 1

EFFECT OF FREEZING AND TESTING TEMPERATURES ON FLEXURAL STRENGTH

Beam dimensions: 4 by 4 by 43 in.
Span: 40 in.
Loading: 4-pt bending

Pulp content: 4%
Test speed: 1.0 in./min.

	Strength, psi			
Frozen at	15°F	0°F	15°F	0°F
Tested at	15°F	15°F	0°F	0°F
	880	1130	1025	920
	935	905	1100	1080
Average	905	1015	1060	1000

TABLE 2

EFFECT OF PULP CONTENT AND TESTING RATE ON FLEXURAL STRENGTH

Beam dimensions: 4 by 4 by 43 in.
Span: 40 in.
Loading: 4-pt. bending

Pulp contents: 4, 6, and 8%
Test speed: 0.1 in./min.

	Strength, psi			
Test Temperature	15°F		0°F	
Test speed	0.1 in./min	1.0	0.1	1.0
Pulp Content				
4%	750	850	815	930
6%	675	775	790	960
8%	815	890	840	960

TABLE 3

FAILURE STRENGTH OF BEAMS OF VARIOUS PULP CONTENTS

Beam dimensions: 4 by 4 by 43 in.
Span: 40 in.

Loading: 4-pt. bending
Test speed: 0.1 in./min.

Each result represents test of 1 beam

Temperature	Strength, psi, at temperatures 15° F	0° F
Series No.		
	1% Pulp	
19 BA and BB	205	325
	2% Pulp	
18 BA and BB	400	455
	4% Pulp	
7BA and BB	835	695
7 BA and BB	710	655
7 BA and BB	905	835
6 BA and BB	785	885
8 BA	615	-
8 BA	840	-
8 BA	740	-
8 BA	680	-
8 BA	715	-
8 BA	720	-
8 BA and BB	545	760
8 BA and BB	720	835
8 BA and BB	520	715
9 AA and AB	720	720
9 BA and BB	695	840
14 AA and AB	725	905

TABLE 3 (Continued)

Temperature	Strength, psi 15° F	0° F
Series No.		
14 AA and AB	620	770
15 BA and BB	750	815
21 AA and BB	650	765
24 BA and BB	660	680
24 BA and BB	575	655
43 BA and BB	625	655
43 BA and BB	505	605
43 BA and BB	565	715
Average	680	710
	6% Pulp	
11 AA and BB	695	760
16 BA and BB	675	790
20 BA and BB	605	675
20 BA and BB	750	680
20 BA and BB	685	690
20 AA	560	-
20 AB	-	880
20 BB	-	825
22 BA and BB	750	850
22 BA and BB	635	730
41 AA and BB	665	740
41 AA and BB	755	715
41 AA and BB	690	730
44 BA and BB	620	725
44 BA and BB	605	670
44 BA and BB	660	655
51 BA and BB	550	605
51 BA and BB	530	645
Average	650	725

TABLE 3 (Continued)

Temperature	Strength, psi 15° F	Strength, psi 0° F
Series No.		
	7% Pulp	
12 BA and BB	750	875
	8% Pulp	
10 AA and BB	828	970
13 BA and BB	855	965
17 BA and BB	815	840
17 BA and BB	655	720
26 BA and BB	680	750
26 BA and BB	695	720
45 BA and BB	580	770
45 BA and BB	665	570
45 BA and BB	595	695
Average	715	765
	10.5% Pulp	
55 BA and BB	750	775
55 BB	-	750
	14% Pulp	
57 BB	-	990
57 BB	-	905

TABLE 4

FLEXURAL STRENGTH AS INFLUENCED BY POSITION OF FROZEN FACE OF BEAM DURING TEST

Beam dimensions: 4 by 4 by 43 in.
Span: 40 in.

Test speed: 0.1 in./min
Loading: 4-pt bending

	Strength, psi	
	Frozen face up	Frozen face at side
4% pulp, tested at 15°F	615	680
	840	740
Average	730	710
	Frozen face up	Frozen face at bottom
6% pulp, tested at 0°F	600	745
	680	700
	700	735
Average	660	725

TABLE 5

FLEXURAL TESTS ON LARGE BEAMS

Beam dimensions: 4 by 8 by 85 in. (beams cast in 2 layers)
Span: 80 in.
Loading: 4-pt. bending Test speed: 0. 1 in. /min.

	Strength, psi	
Temperature	15° F	0° F
4% Pulp	340	600
	410	695
	455	460
Average	400	585
6% Pulp	440	625

TABLE 6

FLEXURAL TESTS OF BUILT-UP (WELDED) BEAMS

(See Photo 13)

Beam dimensions: 4 by 8 by 85 in. Loading: 4-pt. bending
Span: 80 in. Test speed: 0. 1 in. /min

	Strength, psi			
Temperature of Test	15° F		0° F	
	Original Test	Rewelded	Original Test	Rewelded
4% Pulp	400	300	500	410*
	585	470	485	360

* Broke outside of weld in 2nd test.

TABLE 7

COMPRESSION TESTS ON 4-IN. CUBES

Test speed: 0.1 in./min. except as indicated

Temperature	Compressive strength, psi 15°F		0°F	
Load Applied	Parallel	Perpendicular	Parallel	Perpendicular
Series No.				
		1% Pulp		
19	830	1040	970	1290
		2% Pulp		
18	990	975	1100	1380
18	950	950	-	-
		4% Pulp		
1	990	1110	1225	1550
1(1.0"/min)	1110	1340	1850	2420
2	940	1270	1260	1440
2(1.0"/min)	1240	1520	1750	2400
3	950	1310	1350	1600
4	975	1205	1160	1440
5	985	1120	1310	1510
6	905	1200	1020	1165
7	1000	1190	1240	1520
6	-	-	1310	1670
9	-	-	1180	1420
15	955	1140	1210	1420
21	850	1095	1170	1470
40	985	1050	1180	1280
40	960	995	1220	1310

TABLE 7 (Continued)

	Compressive strength, psi			
Temperature	15° F		0° F	
Load Applied	Parallel	Perpendicular	Parallel	Perpendicular
Series No.				
24	955	1175	1320	1840
24	875	1130	1370	1805
8	970	1225	1220	1450
8	945	1255	1385	1400
Average 0. 1''/min.	950	1160	1235	1480
		6% Pulp		
11	960	1140	1345	1610
16	935	1270	1205	1610
20	1090	1130	1310	1775
20	1000	1180	1335	1740
20	-	-	1275	1665
22	1005	1205	1375	2010
22	1005	1205	1445	1880
41	980	1015	1125	1625
41	955	1025	1180	1590
51	1035	1410	1410	1750
51	1160	1375	1420	1670
Average	1010	1195	1320	1720
		7% Pulp		
12	1070	1290	1370	1600
		8% Pulp		
10	1080	1140	1245	1410
10	990	1105	1450	1480

TABLE 7 (Continued)

	Compressive strength, psi			
Temperature	15° F		0° F	
Load Applied	Parallel	Perpendicular	Parallel	Perpendicular
Series No.				
13	1180	1215	1460	1475
17	930	1145	1340	1540
26	1085	1245	1450	1875
26	1065	1280	1420	1860
Average	1055	1190	1435	1610
		10.5% Pulp		
55	-	-	1540	1645
55	-	-	1530	1625
		14% Pulp		
57	1170	1200	1490	1560
57	1210	1005	1515	1545
River Ice	765	860	1215	1240
" " "	760	905	1055	1195
" " "	775	955	-	1255
" " "	-	-	-	1180
Average	765	905	1055	1195
Frozen Tap Water	1025	935	1200	850
" " " " "	650	600	1085	590
" " " " "	725	530	-	-
" " " " "	827	770	-	-
" " " " "	725	615	-	-
Average	790	690	1140	720

The results of tests on frozen tap water are inconsistent with relative values usually obtained for the two directions of applied load. The inverted results were not due to errors in marking the test specimens prior to test.

TABLE 8

COMPRESSION TESTS ON FROZEN PULP CYLINDERS

Dimensions of test specimens: 3.3 in. in diam. by $6\frac{1}{2}$ in. high
Test speed: 0.1 in./min

		Compressive strength, psi			
Pulp Content	Frozen at / Tested at	15° F / 15° F	0° F / 15° F	15° F / 0° F	0° F / 0° F
		1150	1105	1535	1390
4%		1150	1130	1460	1460
		1035	1140	1440	1380
	Average	1110	1130	1480	1410
		1075	1130	1425	1395
6%		1100	1150	1440	1450
		1120	1160	1510	1425
	Average	1130	1145	1525	1410
		985	1080	1450	1390
8%		1025	1135	1450	1430
		1060	1195	1590	1490
	Average	1025	1135	1495	1430

TABLE 9

COMPRESSION TESTS OF FROZEN PULP PRISMS
USED IN SPECIFIC GRAVITY TESTS

Dimensions of prisms: 4 by 4 by 8 in. approx.
Test speed: 0.1 in./min

Series	Pulp Content		Compressive strength, psi 15°F Parallel to Freezing Surface
43	4%		865
			870
			880
		Average	870
44	6%		920
			940
			940
		Average	935
45	8%		930
			930
			950
		Average	940
55	10.5%		940
			930
			955
			960
			920
		Average	940
57	14%		950
			960
		Average	955

TABLE 10

TENSION TESTS OF FROZEN PULP (SLOW FREEZE)

Test specimens: cross-section 6 in. square, approx.
Test speed: 0.1 in./min

	Tensile strength, psi					
	15° F			0° F		
Pulp Content	Orig. Test	1st Weld	2nd Weld	Orig. Test	1st Weld	2nd Weld
	258	370		340	320	
	284	271		350	368*	
4%	288	334*	170	369	343	
	346	244		394	288*	394
	352	344*		405	337	
Average	305	310		370	331	
	260	423*	274	335	258	
	313	288		366	342	
6%	354	394*	352	425	325	
	390	325*		475	296	
	480	410		515	475	
Average	350	368		425	340	
	466	-		520	438	
8%	- **	328		410	348	
	450	352		445	460*	342
Average	458	340		490	415	
6 quick freeze (3/8" layers in wind tunnel)				435	342	
14 quick freeze (3/8" layers in wind tunnel)				645	252*	
				700		
				690		
14 slow freeze (2" layer)				625	442	
				520		

Note: * Broke outside of weld on retest

** Broken in handling, before first test.

TABLE 11

TENSION TESTS OF FROZEN PULP (SLOW FREEZE)

Test specimens: cross-section 8 in. square, approx.
Test speed: 0.1 in./min.

	Tensile strength, psi			
	15° F		0° F	
Pulp Content	Orig. Test	1st Weld	Orig. Test	1st Weld
4%	292			
	315		300	320*
	305	274	244	240
Average	304		272	280
6%	246	270*	266	270
	368	365	465	300
	400	275	425	255
	318	305	410	355
			340	345
Average	333	304	381	305
8%	394	340	415	225
	353	285	435	415
	422	325	432	90*
Average	390	316	427	

Note: * - Broke outside of weld

TABLE 12

TENSION TESTS OF FROZEN PULP (SLOW FREEZE)

Test specimens: molded vertically in layers with ice planes with welds normal to direction of loading
Test speed: 0. 1 in. /min

	Tensile strength, psi
Pulp Content	15° F
	270
4%	410
	420
	120
	195
	270
6%	275
	240
	355

TABLE 13

QUICK BOND TESTS OF WOOD IN FROZEN PULP

Test speed: 0.1 in./min Pulp content: 6%

Temperature of Test			Computed bond stress, psi
15° F	-1/2" diameter round birch dowels		410
			415
			440
			445
			465
			490
		Average	444
	-1/2" square white pine D2S		340
			370
			405
		Average	372
	-3/4" square larch D2S		280
			290
			340
		Average	305
0° F	-1/2" diameter birch	2 failures	590
		in bond	690
		Average	640
	-4 failures in wood in compression		
		Average	520
	-1/2" square white pine 6 failures of wood in compression		
		Average	361
	-3/4" square larch	2 bond failures	358
			445
		Average	400

TABLE 14

QUICK BOND TESTS OF STEEL IN FROZEN PULP

Test speed: 0. 1 in. /min Pulp content: 6%

Temperature of Test			Computed bond stress, psi
15° F	-1/2" diameter steel rod		116
			117
			122
			134
			136
			157
			159
		Average	134
	-1/4" diameter steel rod		76
			76
			77
			96
			132
			175
		Average	105
0° F	-1/2" diameter steel rod		156
			160
			164
			178
			183
			191
		Average	171
	-1/4" diameter steel rod		102
			193
			209
			215
			239
		Average	191

TABLE 15

SHEAR STRENGTH OF WELDED JOINTS

(See Photo 10)

Area of shear: 23 sq in., approx.   Test speed: 0.1 in./min

% Pulp in Weld Mortar		Shear strength, psi Tested at 15°F	Shear strength, psi Tested at 0°F
		340	465
		430	470
4		430	480
		390	510
		375	555
	Average	393	496
		435	440
		440	480
6		410	575
		380	585
		480	605
	Average	415	537
		410	530
		455	550
8		455	565
		470	585
		480	- (base failed)
	Average	454	556

TABLE 16

SHEAR STRENGTH OF HOMOGENEOUS FROZEN PULP

Test specimens cut from 4- by 8-in. beams
Area of shear: 15 sq in., approx
Test speed: 0.1 in./min

		Shear strength, psi	
% Pulp		15°F	0°F
4		635*	715
		570	865
		680	920
	Average	662	833

* See Photo No. 11. When test was stopped specimen appeared as in photograph and was still carrying 510 psi (based on original area)

TABLE 17

TENSION TESTS ON WHITE PINE REINFORCEMENT

Test specimens: 1/2 in. sq., ends embedded in frozen pulp
Test speed: 0.1 in./min.

	Tension strength, psi
Four rods - selected at random	4600
	7900
	9400
	12250

TABLE 18

FREEZING TESTS ON PULP IN WIND TUNNEL

(See Diagram 1)

Equipment: Friez air meter, Leeds and Northrup - Potentiometer, copper constantan thermocouples

Pulp Content, %	Thickness of Layers, In.	Temp. of Air, °F	Air Speed	Time, Minutes, for Pulp to Reach 32°F	Additional Time, Minutes for Temp. to Drop Below 32°F	Number of Tests
6	3/8	4	550 ft/min. $6\frac{1}{4}$ m. p. h.	2 to 4	Ave. 71	3
6	3/8	4	1100 ft/min. $12\frac{1}{2}$ m. p. h.	2 to 4	Ave. 47.5	5
6	3/8	4	0	5	247	1
6	1	4	$12\frac{1}{2}$ m. p. h.	9	138	1
6	3/8	15	$6\frac{1}{4}$ m. p. h.	4 to 6	129 92	1 1
6	3/8	15	$12\frac{1}{2}$ m. p. h.	4 to 6	Ave. 85	3
6	3/8	15	0	5	350	1
14	3/8	4	$6\frac{1}{4}$ m. p. h.	2 to 4	55.5	2
14	3/8	4	$12\frac{1}{2}$ m. p. h.	2 to 4	40.2	6

TABLE 19

FLEXURAL TESTS ON REINFORCED FROZEN PULP BEAMS

Beam dimensions: 4 by 4 by 43 in.
Span: 40 in.

Test speed: 0.1 in./min
Loading: 4-pt bending

% Pulp	Reinforcement	% Reinforcement**	Surface Area per inch of length sq. in.		Strength, psi* 15°F	0°F
4	$\frac{1}{2}$" square white pine D2S in tension	1.56	2.0		955	1010
					1030	910
					1035	825
					-	925
					-	1070
				Ave.	1065	950
6	$\frac{1}{2}$" square white pine D2S in tension	1.56	2.0		-	1035
6	$\frac{3}{4}$" square larch D2S in tension	3.52	3.0		1150	1395
					1060	1270
					1100	1270
				Ave.	1105	1310
6	$\frac{3}{4}$" square larch D2S					
	1 in tension	7.04	3.0		1200	1635
	1 in compression	7.04	3.0		1370	1720
					-	1735
				Ave.	1235	1695
6	$\frac{1}{4}$" diameter round steel straight - no hooks	.30	.785		880	1175
					975	1125
					810	1115
				Ave.	890	1140

(Continued)

TABLE 19 (Continued)

% Pulp	Reinforcement	% Reinforcement**	Surface Area per inch of length sq. in.	Strength, psi* 15° F	0° F
6	$\frac{1}{4}$" diameter round steel ends hooked	.30	.785	885	1100
				815	1030
				840	1100
				900	1100
			Ave.	860	1080

* - Computed as for plain elastic beam

** - Based on beam section of 16 sq in.

TABLE 20

SPECIFIC GRAVITY AND UNIT WEIGHTS OF FROZEN PULP, HOMOGENEOUS AND FREE OF ICE LAYERS

Pulp Content			Specific Gravity	Weight - Cu Ft Lb (Water = 62.5 lb cu ft)
			0.9357	
4%			0.9320	
			0.9344	
		Ave.	0.9340	58.4
			0.9404	
6%			0.9406	
			0.9386	
		Ave.	0.9399	58.7
			0.9407	
8%			0.9413	
			0.9401	
		Ave.	0.9407	58.8
			0.9420	
10.5%			0.9489	
			0.9435	
		Ave.	0.9448	59.0
14%	3/8" layers quick		0.9524	
	freeze in wind tunnel		0.9663	
		Ave.	0.9593	60.0
14%	Slow freeze		0.9606	
	4" layer		0.9632	
		Ave.	0.9619	60.1
4%	Welded Block approx $12\frac{1}{2}$" x $12\frac{1}{2}$" x 16" sent to Quebec in August			58.2
6%	Welded Block approx 12" x $12\frac{1}{2}$" x $16\frac{1}{2}$			59.5

TABLE 21

PLASTIC FLOW IN COMPRESSION PER CENT PER YEAR

Except where more than one value is given, the rate is for the first 200 hours. Other values are for longer time intervals.

15°F

Load, psi

		100		200		300		400
4%	Parallel	24-1	0.39	24-H	14.50	24-E	304.0	
		27-1	1.31	24-1-x*	11.45	27-F	196.0	
	Perpendicular	24-2	0.87	24-I	10.10	24-O	140.0	
		27-5	1.31					
6%	Parallel	20-1	1.45	22-1	5.46*		35.4	20-D^{+}
				20-F	(9.20		38.4	
					(6.85			
				53-2	3.41^{++}			
		20-2	1.53	22-2	3.08*	28-G	(8.00	
							(3.96	
	Perpendicular	28-4	0.79	20-6	5.70			
					1.75	28-2	4.58	20-E^{+}
		28-1	1.40*					
8%	Parallel	26-1	1.00	26-0	9.85			
		30-1	0.96					
	Perpendicular	26-2	0.83	26-K	9.90	26-H	(17.8	
		30-4	0.49				(12.9	

River Ice		50 psi	75 psi
	Parallel	20.80**	63.5
	Perpendicular	2.62	5.25

Notes: * - Tests continued beyond 200 hours. See Table 22

** - Sides were wrinkling or corrugating. See photo No. 22.

+ - Failed before any readings were taken.

++ - Reinforced with ½" sq wooden rod, Test continued.

TABLE 21 (Continued)

0° F

Load, psi

		100		200		300		400	
4%	Parallel	24-4	1.62			24-N	(15.10	24-F	139.0
		27-2	1.14				(10.70		
	Perpendicular	24-3	1.07			24-0	-- +	24-6	-- +
		27-6	1.14						
6%	Parallel	20-3	0.26	22-1-X	3.32*	20-N	(12.1	20-H	35.8
		28-2	1.40*	22-3	3.19*		(6.1	28-F	29.0
				53-1	3.50++				
	Perpendicular	20-4	1.31	22-4	2.19*	20-0	(8.30	20-I	20.50
							(4.56		
		28-5	0.39					28-H	(8.45
									(6.37
8%	Parallel	26-4	1.61			26-E	16.9		
		30-2	1.31						
	Perpendicular	26-3	0.17			26-L	(3.72		
		30-5	1.31				(2.80		
							(1.18		

River Ice		50 psi	75 psi
	Parallel	24.90**	116.0
	Perpendicular	2.92	5.57

Notes: * - Tests continued beyond 200 hours. See Table 22.
** - Sides were wrinkling or corrugating. See Photo No. 22.
+ - Failed before any readings were taken
++ - Reinforced with $\frac{1}{2}$" sq wooden rod. Test continued.

TABLE 22

DECREASE IN RATE OF PLASTIC FLOW WITH TIME

(Rate per year in per cent; see also Table 21)

Pulp Content	Series No.	Temp. °F	Direction of Load	Load psi	Rate per Year 1st 200 hours % (These values appear in Table 21)	Later Rates of Flow	
4%	24-1-x**	15	Parallel	200	11.45	6.04 (300 - 700 hours)	3.40 (700 - 1500 hours)
6%	28-1	15	Parallel	100	1.40	0.49 (470 - 670)	0.39 (700 - 1500)
	28-2	0	Parallel	100	1.40	0.39 (470 - 670)	0.12 (700 - 1500) 0.00 (last 600 hours)
	22-1-x	0	Parallel	200	3.32	0.87 (300 - 700)	0.55 (600 - 1500)
	22-1	15	Parallel	200	5.46	2.62 (250 - 450)	0.75 (700 - 1300)
	22-2	15	Perpendicular	200	3.08	1.49 (250 - 450)	0.46 (700 - 1300)
	22-3	0	Parallel	200	3.19	2.05 (250 - 450)	0.76 (700 - 1300)
	22-4	0	Perpendicular	200	2.19	1.27 (250 - 450)	0.00 (700 - 1300)
	53-1*	15	Parallel	200	3.50	0.87 (200 - 400)	0.34 (400 - 1200)
	53-2*	0	Parallel	200	3.41	0.87 (200 - 400)	0.33 (400 - 1200)
8%	26-L+	0	Perpendicular	300	3.72	2.80 (200 - 400)	1.18 (590 - 790)

Note: * - $1\frac{1}{2}$" sq wooden reinforcement.
** - Considerable eccentricity of loading - readings on 1 side increased. Early preliminary test with 22-1-x showed same rates for both.
\+ - 2" x 2" x 6" specimen. Probably loaded with little or no eccentricity. See Photo No. 15 for behaviour of this size of specimen in test.

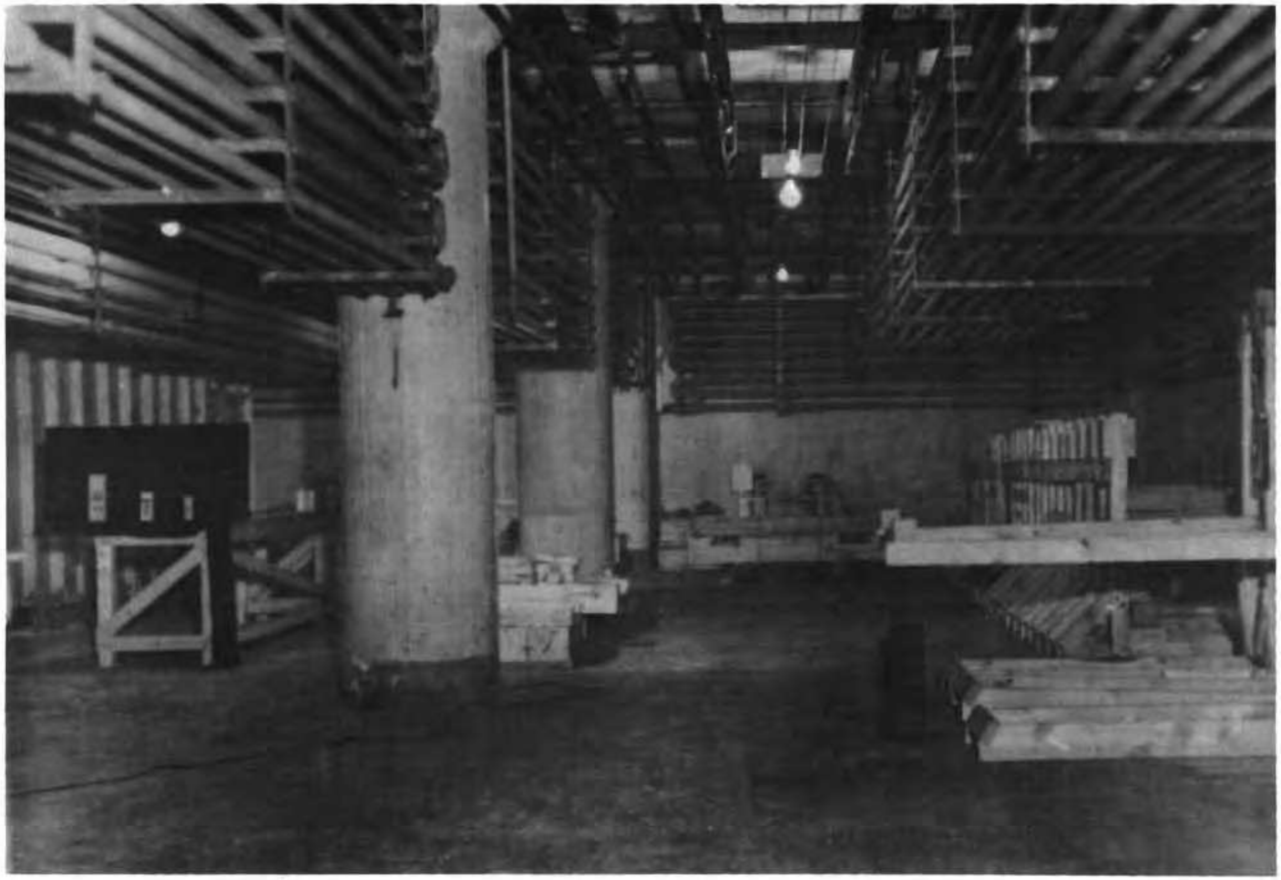

Photo No. 1. View of 15° F room. Work tables at left and on right side, 19 sustained loading testing machines for beams and tension and compression specimens. 0° F room behind wall at left contains 15 more testing machines. Temperature of 15° was maintained by occasionally opening valve controlling frost covered pipes near left ceiling. Remainder of nearly 4 miles of 2-in. pipe was unused.

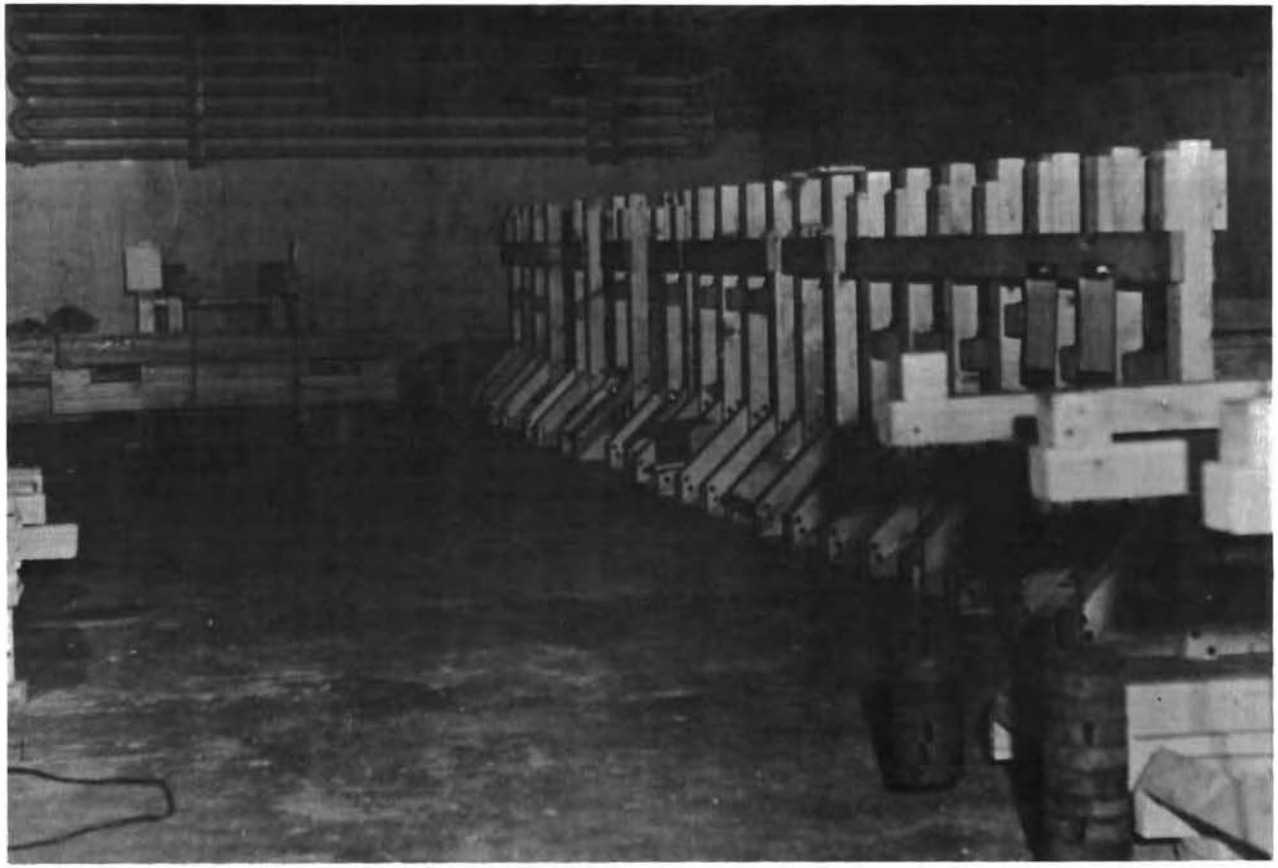

Photo No. 2. Another view of 15° F room and loading frames.

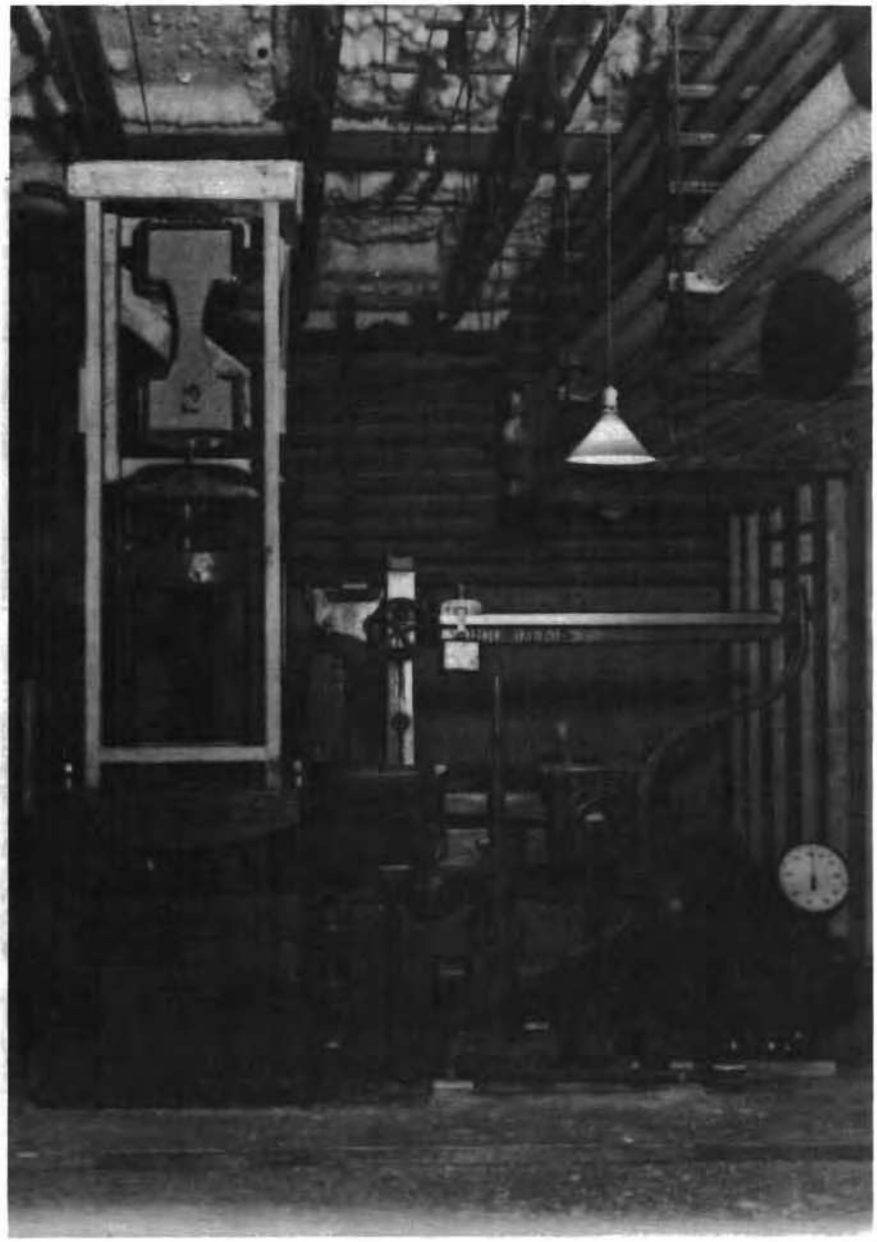

Photo No. 3. Riehle power testing machine obtained from McGill University for making quick tests. This is a two-screw machine with capacity of 60, 000 lb. Speed accurately controlled by means of tachometer on motor. View shows frame used to adapt machine for tests of large tension specimens.

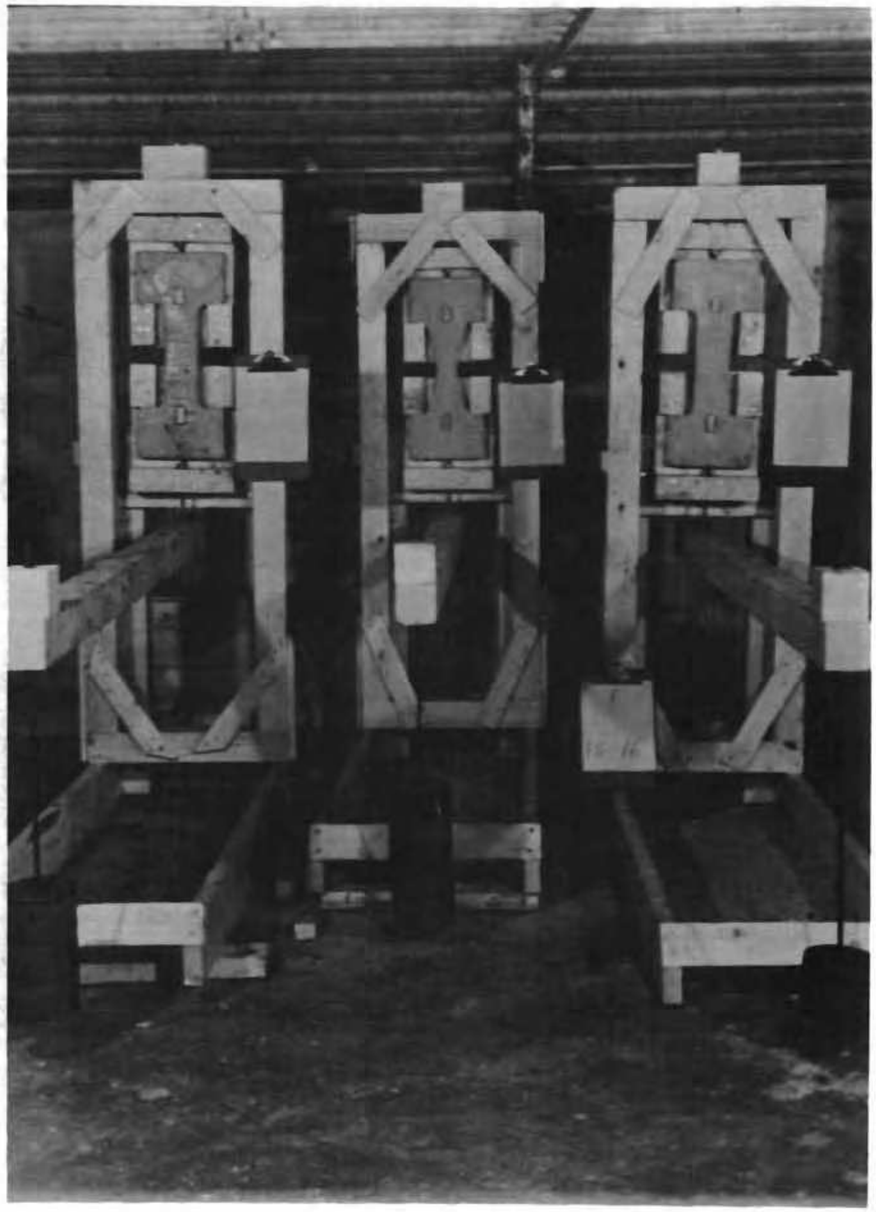

Photo No. 4. Plastic flow of tension test pieces. Gauge points 12 in. apart. Measurements made between nail heads in wooden blocks frozen on face of test specimen.

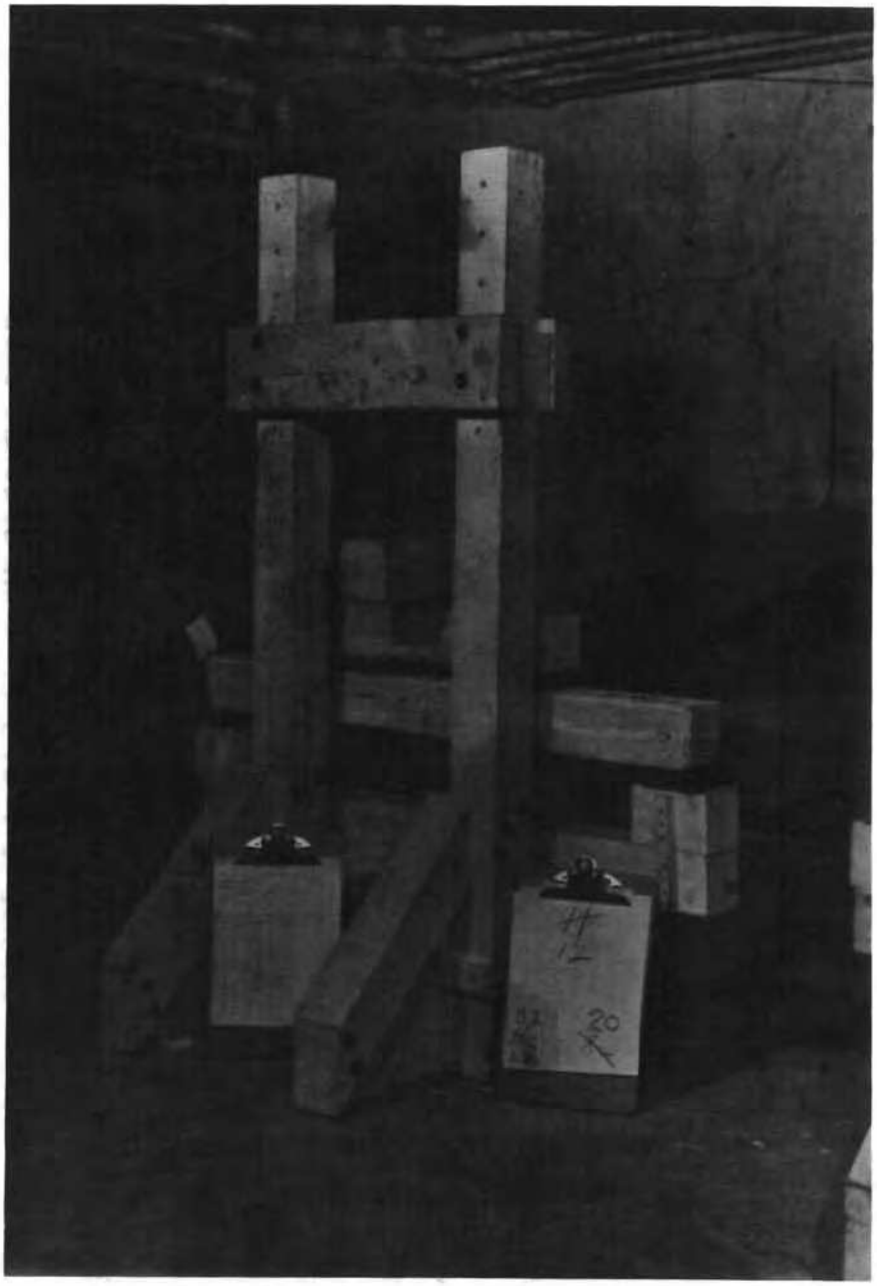

Photo No. 5. Sustained load testing machine adapted for four point loading of small beams. Metal knife edges attached to loading beam insure a leaver ratio of 10 to 1. Beam, without added weights, results in fibre stress of 100 psi. Load adjusted by adding cast iron scale weights of 10, 5, 2 or 1 lb. See Diagram No. 15 for details of loading frames.

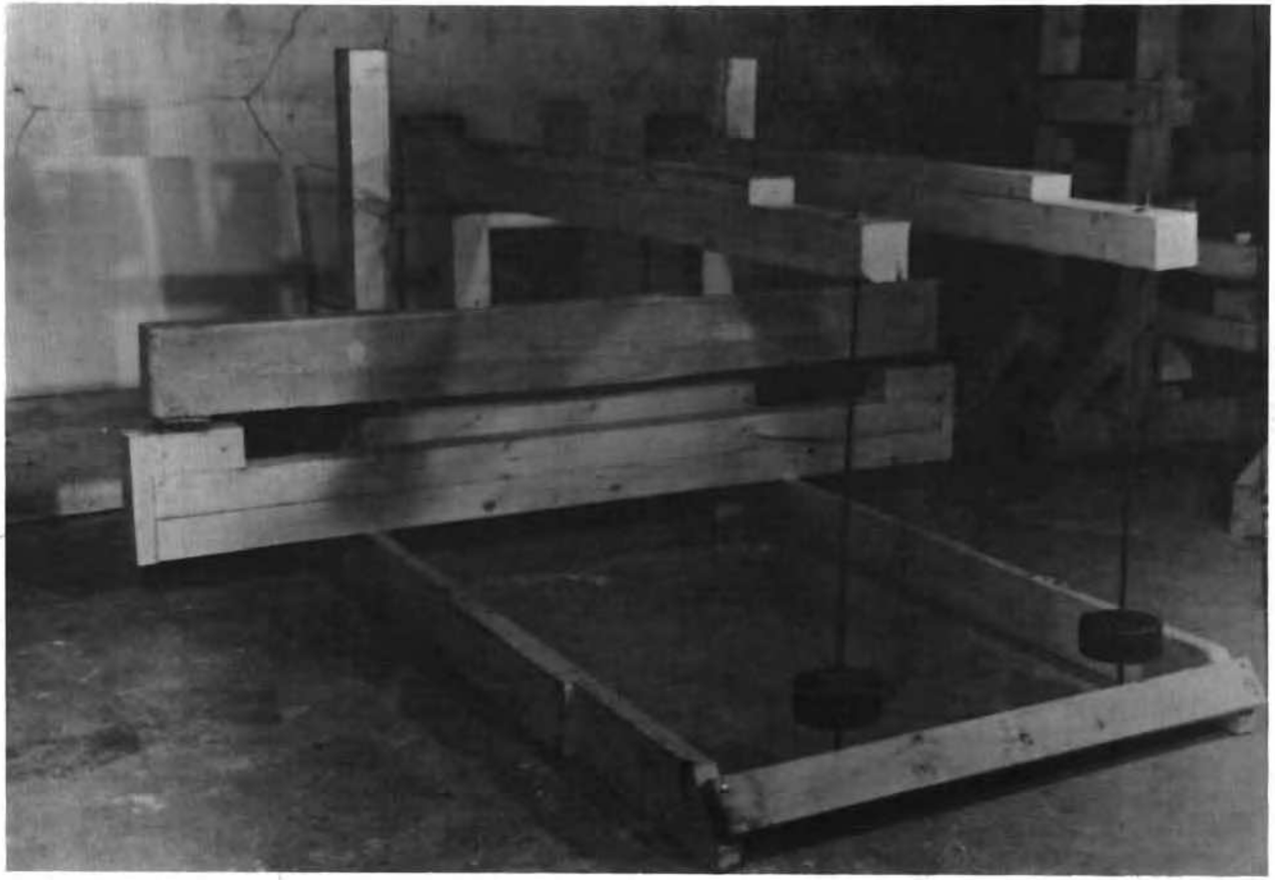

Photo No. 6. Sustained loading of 4- by 8-in. beam of 80-in. span (See Diagrams Nos. 10 and 11). Deflections were near 3/4" when test was discontinued. Flexural stress 200 psi.

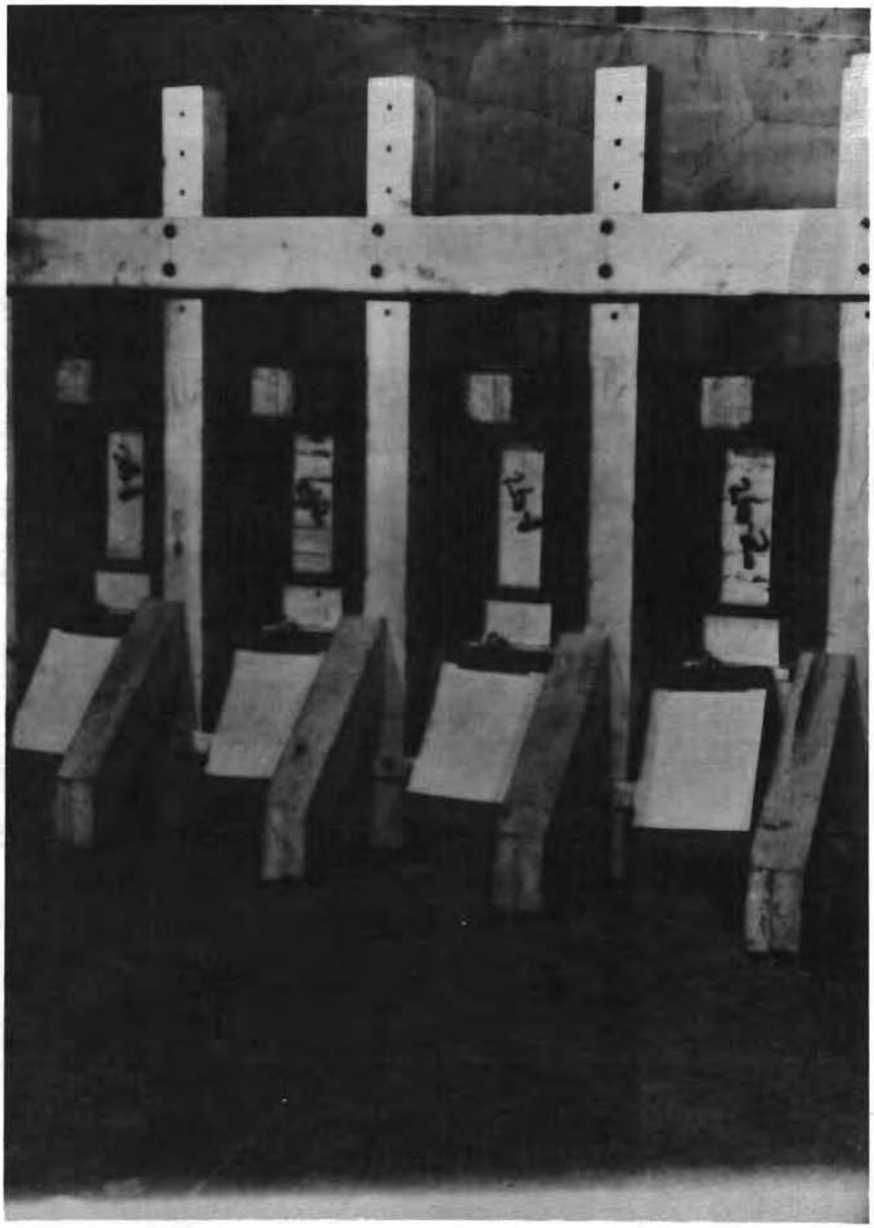

Photo No. 7. Plastic flow in compression. Load 100 psi. Series 24 is 4 per cent; series 26 is 8 per cent. Specimens 24-1 and 26-1 are loaded parallel to frozen surface. Specimens 24-2 and 26-2 are built up of 3 cubes each, with load applied perpendicular to the frozen surface. See Table 21.

Photo No. 8. Compression specimens. Left to right, river ice loaded to 50 and later 75 psi. Specimen 53-1 is reinforced with wood; 28-1 is 4 per cent pulp carrying 100 psi and specimens at right are of 6 per cent pulp carrying 200 psi. Three specimens at right are covered with waxed paper to prevent evaporation. See Tables 21 and 22.

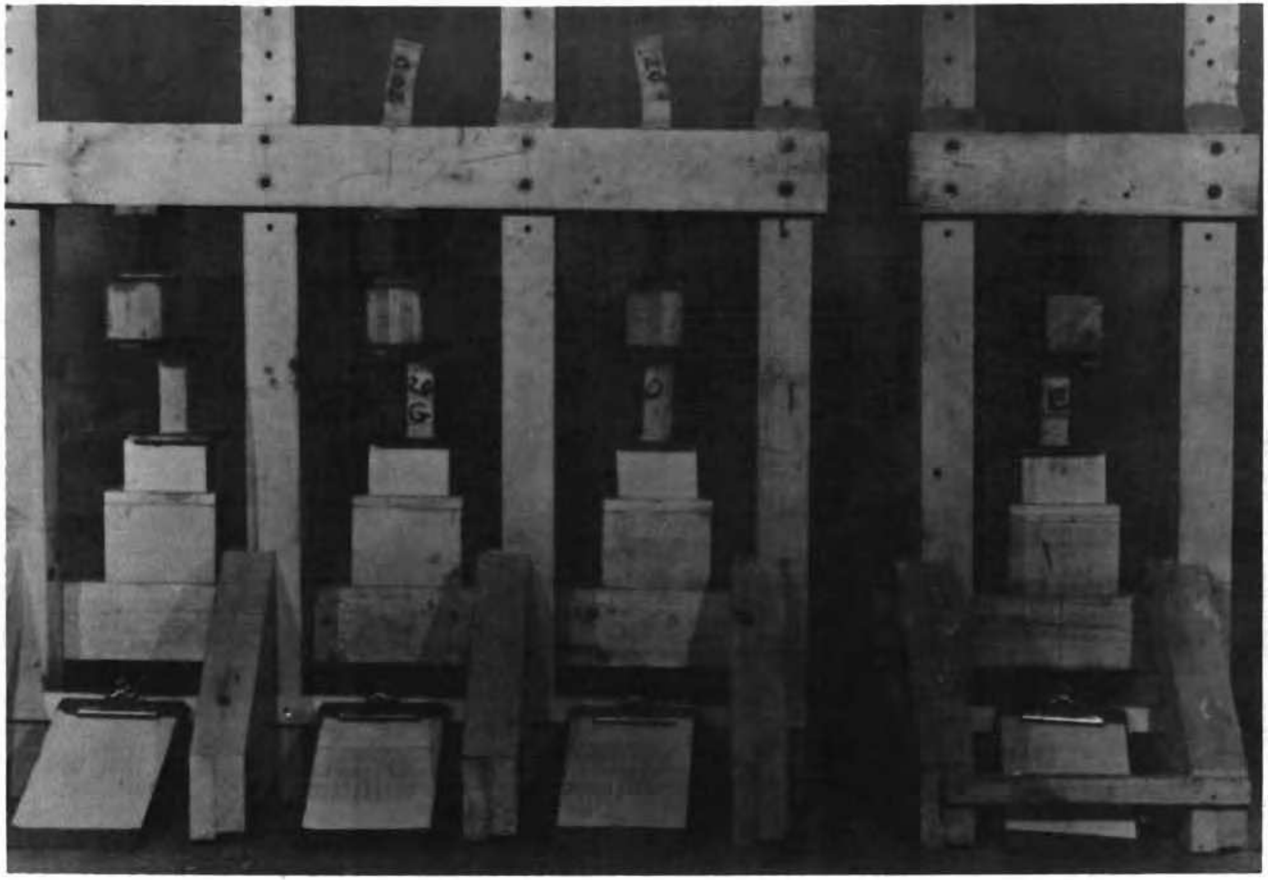

Photo No. 9. Small compression specimens loaded to 200 and 300 psi. Two failed specimens are on top of frame. Slight eccentric loading resulted in high bending stresses. See Table 21.

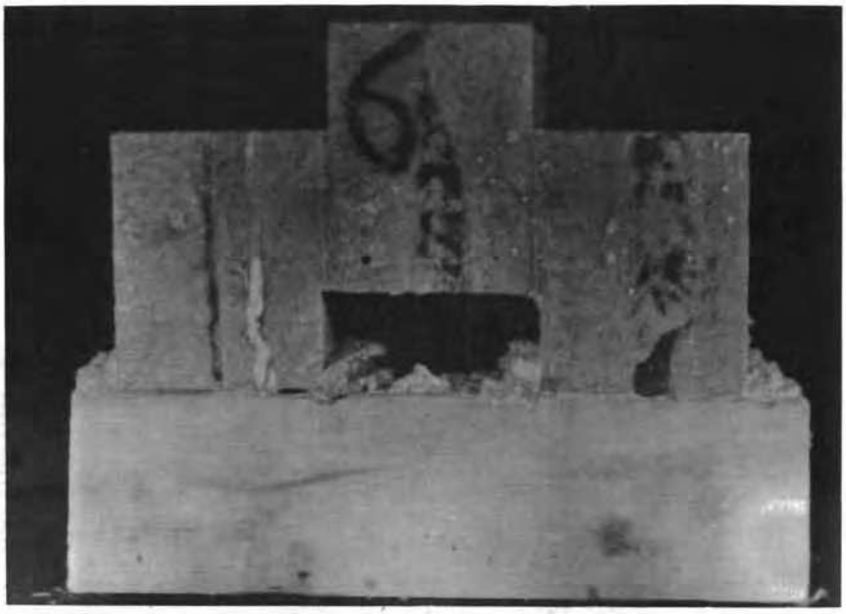

Photo No. 10. Welded shear test specimen, before test. See Table 15.

Photo No. 11. Shear of homogeneous pulp without welds. As shown specimen was still carrying about 80 per cent of maximum load. What appears to be saw cut at top, right side, is vertical face of centre portion which was above level of portion to its right at start of test. See Table 16.

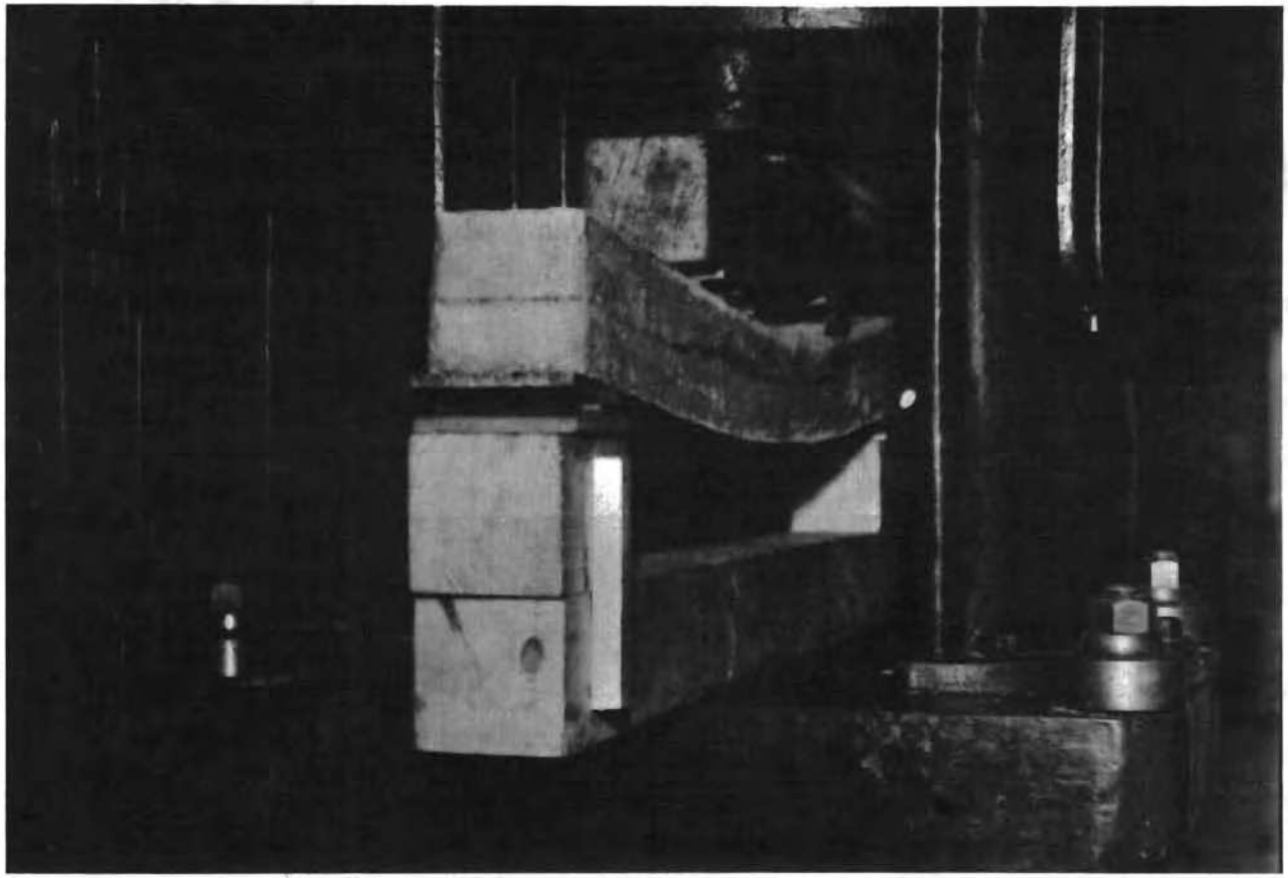

Photo No. 12. Deflection of reinforced beam under test - about 1 in. Final value about $1\frac{1}{2}$in. Note ice seam at top of first 2-in. layer and frozen eruption of water near one third point of span.

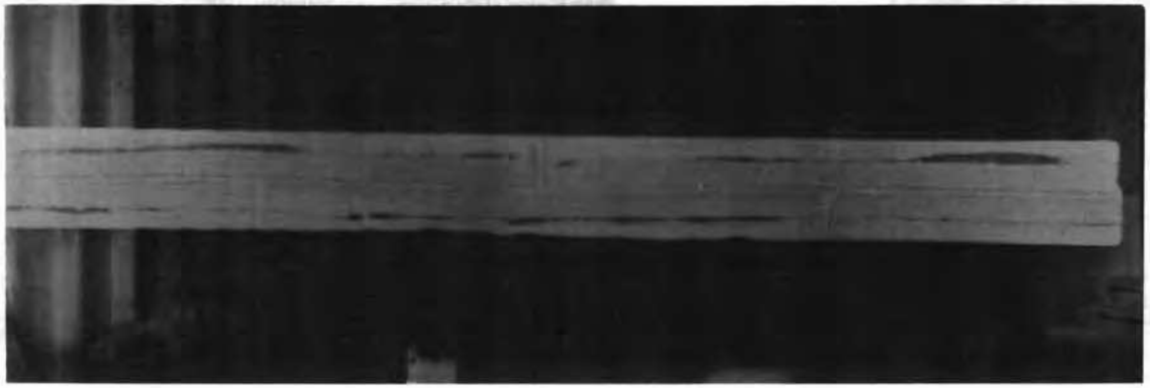

Photo No. 13. Built-up beam 4 by 8 in. with 80-in. span made by welding together 4 smaller beams. 4 per cent pulp. Note ice seams at mid section of small beams which were built up by two 2-in. layers. Parallel dark lines, both vertically and horizontally are due to pure ice at junction of weld pulp and surfaces of beams. After welding surfaces are planed to smooth, glassy finish. See Table 6.

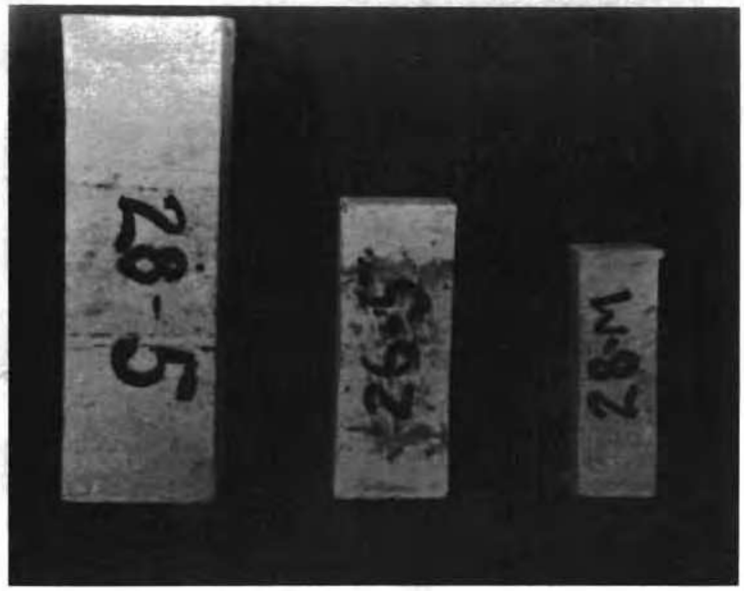

Photo No. 14. Test specimens for plastic flow in compression. At left - 28-5 - 4 by 4 by 12 in. for loading perpendicular to frozen surface. 26-5 is about 2.8 by 2.8 by 7 in. and 28-M is 2 by 2 by 6 in.

Photo No. 15. Typical appearance of 2- by 2- by 6-in. compression pieces after test. Bending stresses increase rapidly as specimen begins to deform and buckle.

Photo No. 16. Beam reinforced with $\frac{1}{4}$-in. round steel rod. Note hook at right end has been pulled into beam. Upper surfaces plane from ends to fracture. Loaded at one third points, beam in this condition was carrying a greater load than at test failure.

Photo No. 17. Enlarged view of right end and hooked reinforcement which was being pulled into beam.

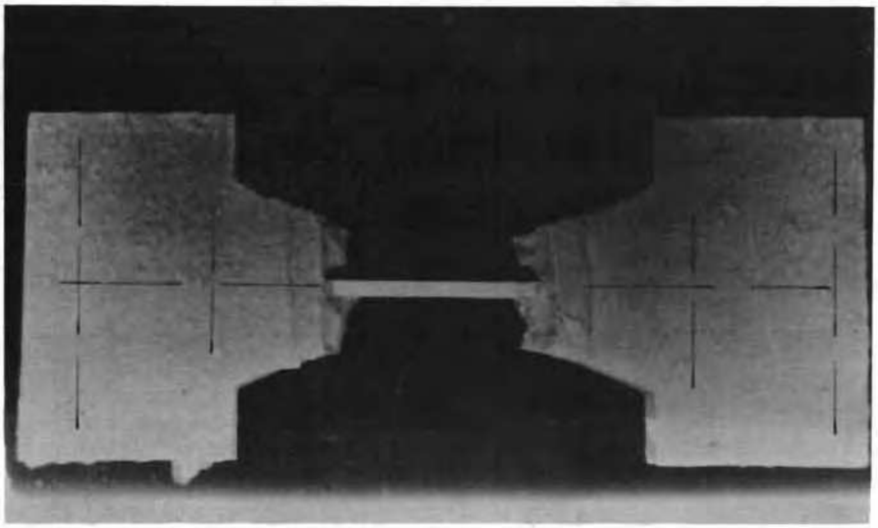

Photo No. 18. Wood in tension. All failed by tension of wood, clear of encased ends. Strength variation was about 300 per cent. See Table 17.

Photo No. 19. Pulp body of lower 2 in. of reinforced beam after thawing and evaporation of water. Note considerable shrinkage. Wood is $\frac{1}{2}$ in. square and as frozen had $\frac{1}{2}$-in. protection below.

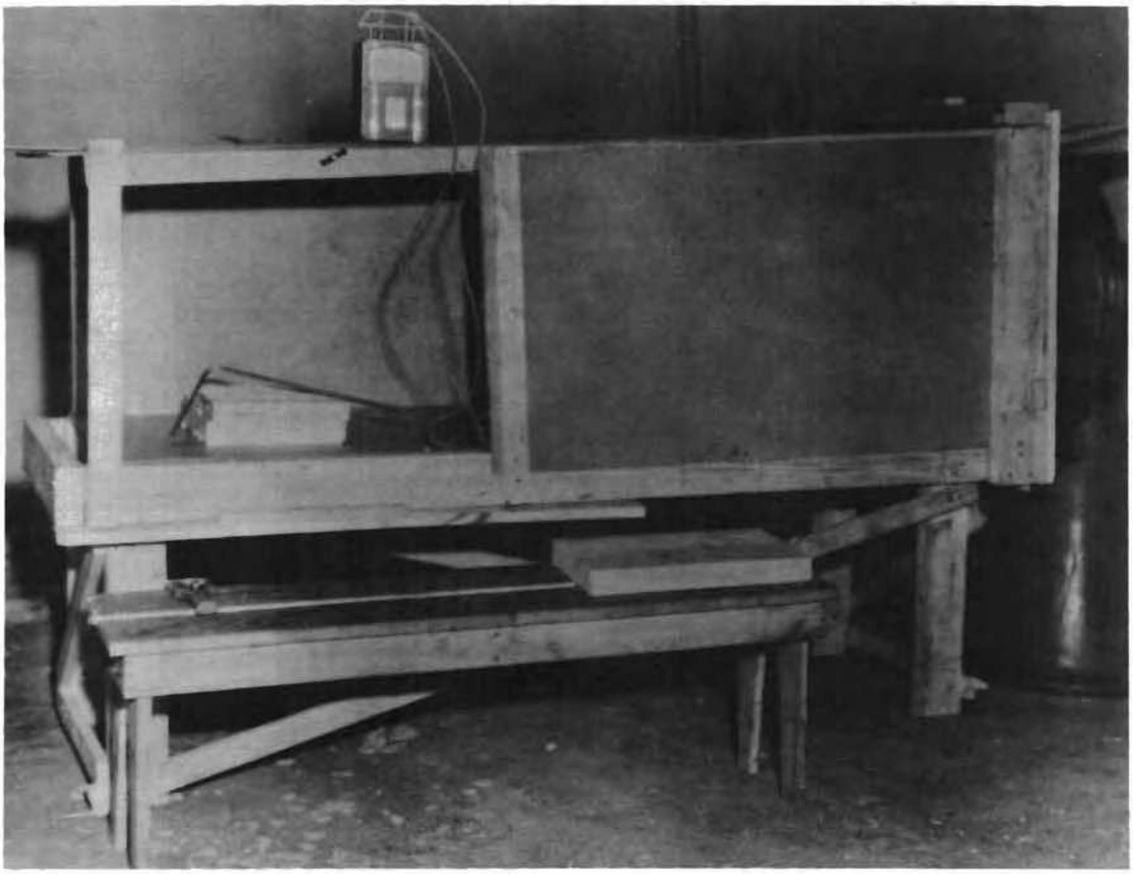

Photo No. 20. Wind tunnel for rapid freezing of test specimens and for determining time required to manufacture, showing fan at right, Friez air meter and method of building up frozen layers. See Table 18 and Diagram No. 1.

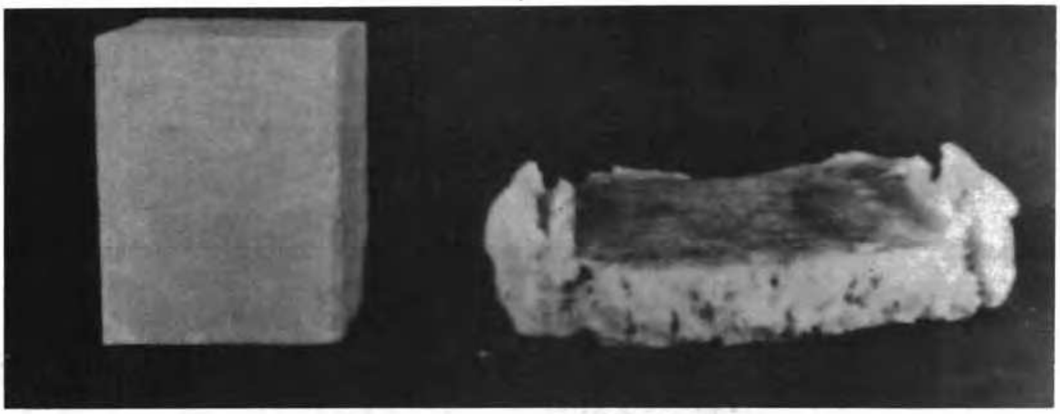

Photo No. 21. Plastic flow with rapid deformation. Specimen at right, originally a 4-in. cube, has been compressed and has spread beyond the 6-in. bearing plates. Unit load at test failure of 795 psi has now increased to 1235 psi based upon area of 36 sq in.

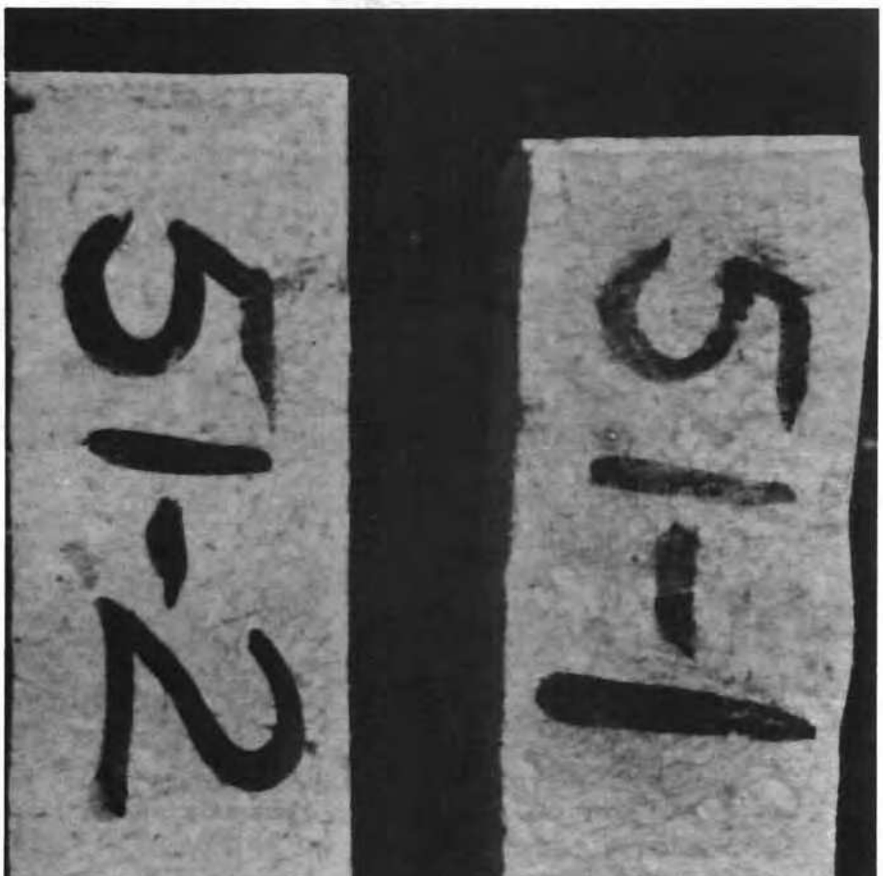

Photo No. 22. Effect of repeated loading and unloading of test piece at right. Note wavy sides and shortening of about $\frac{1}{2}$ in. See section 8a and Diagram No. 3.

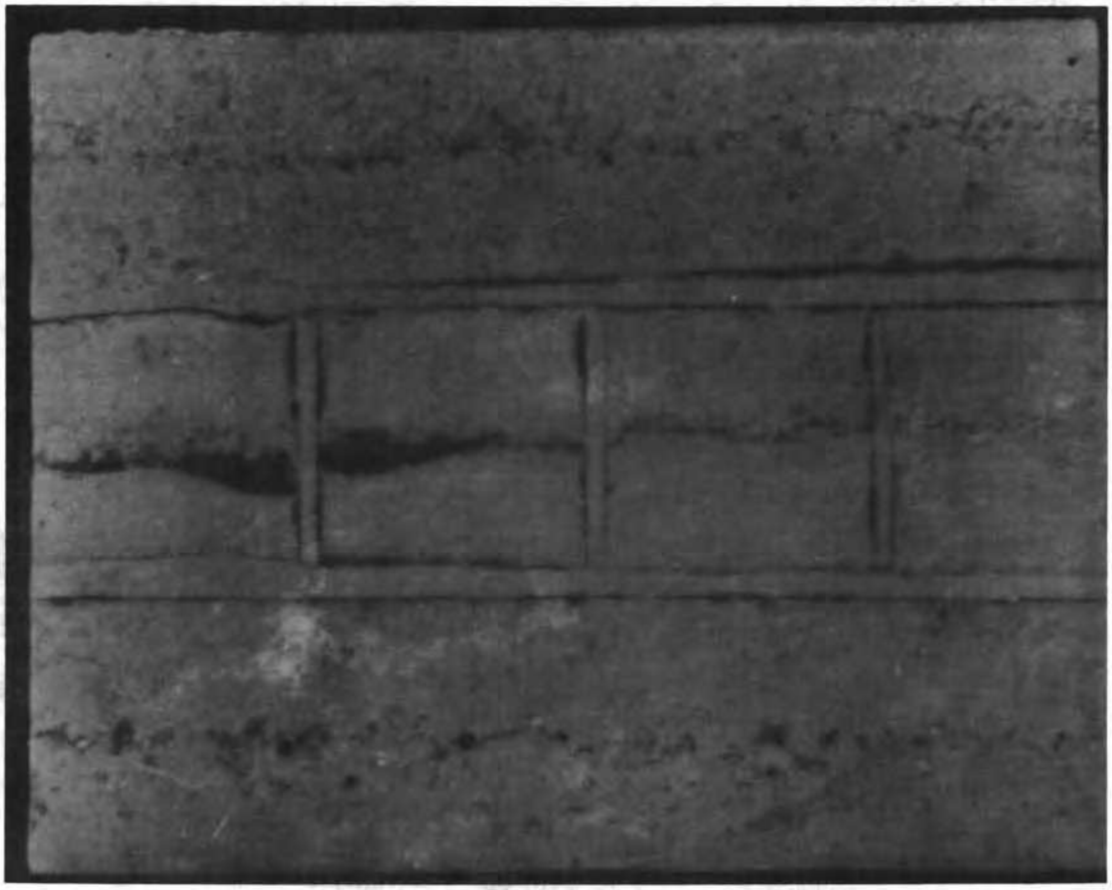

Photo No. 23. One face of built-up 12- by 12- by 16-in. block sent to Quebec in August. Dark spots are not cavities but pure ice. Surface is as smooth as glass. Approximately parallel dark lines are ice layers at surfaces of welding material. Thick ice seams are water eruptions on upper surface of 2-in. pulp layers during freezing of beams.

Photo No. 24. Frozen water forced through upper surface of 2-in. pulp layer. Eruptions sawn through at thickest section. 4, 6 and 8 per cent pulps.

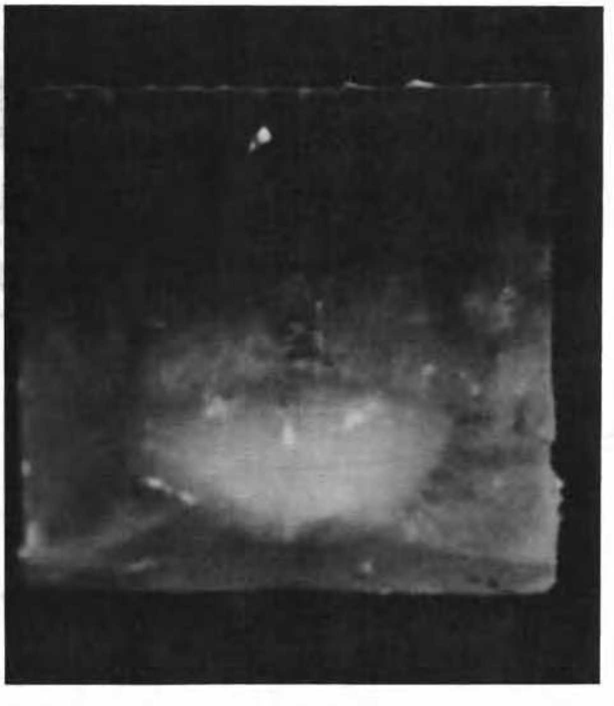

Photo No. 25. Section through a 4- by 4-in. beam of tap water showing opaque portion last to freeze near bottom.

Photo No. 26. Showing appearance of 4, 12 and 14 per cent pulp. Note water which has drained from 4 per cent specimen.

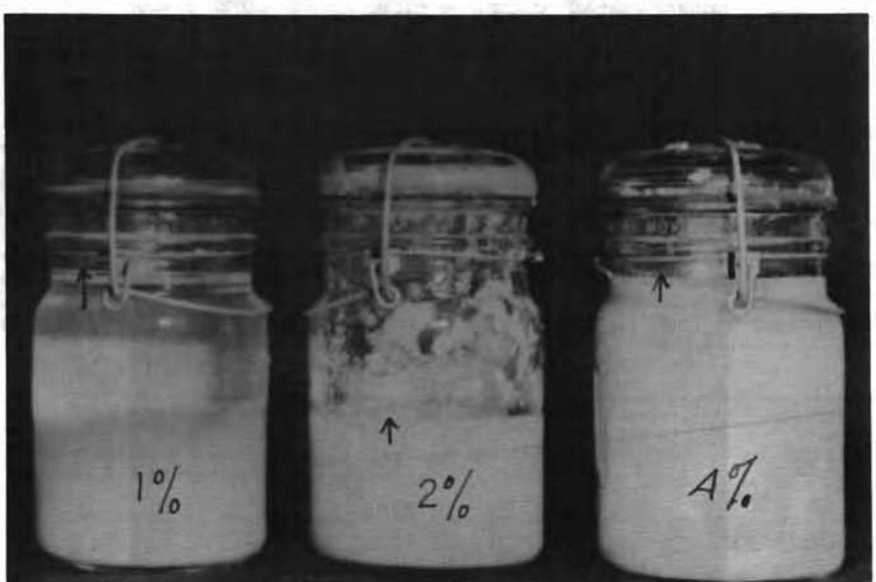

Photo No. 27. Suspensions of 1, 2 and 4 per cent pulps. Arrows indicate water lines.

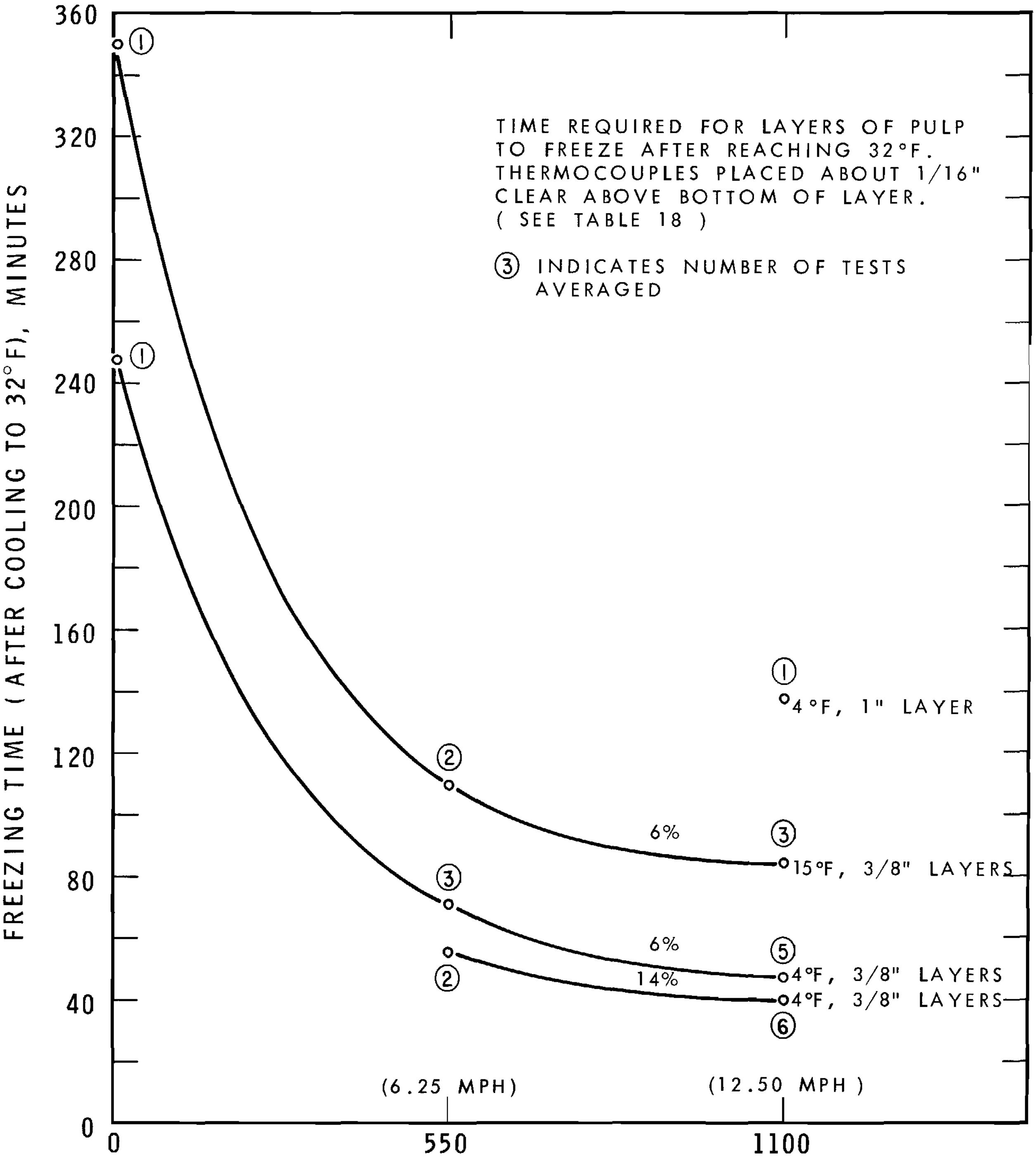

DIAGRAM 1 FREEZING TIMES

BR 4942-1

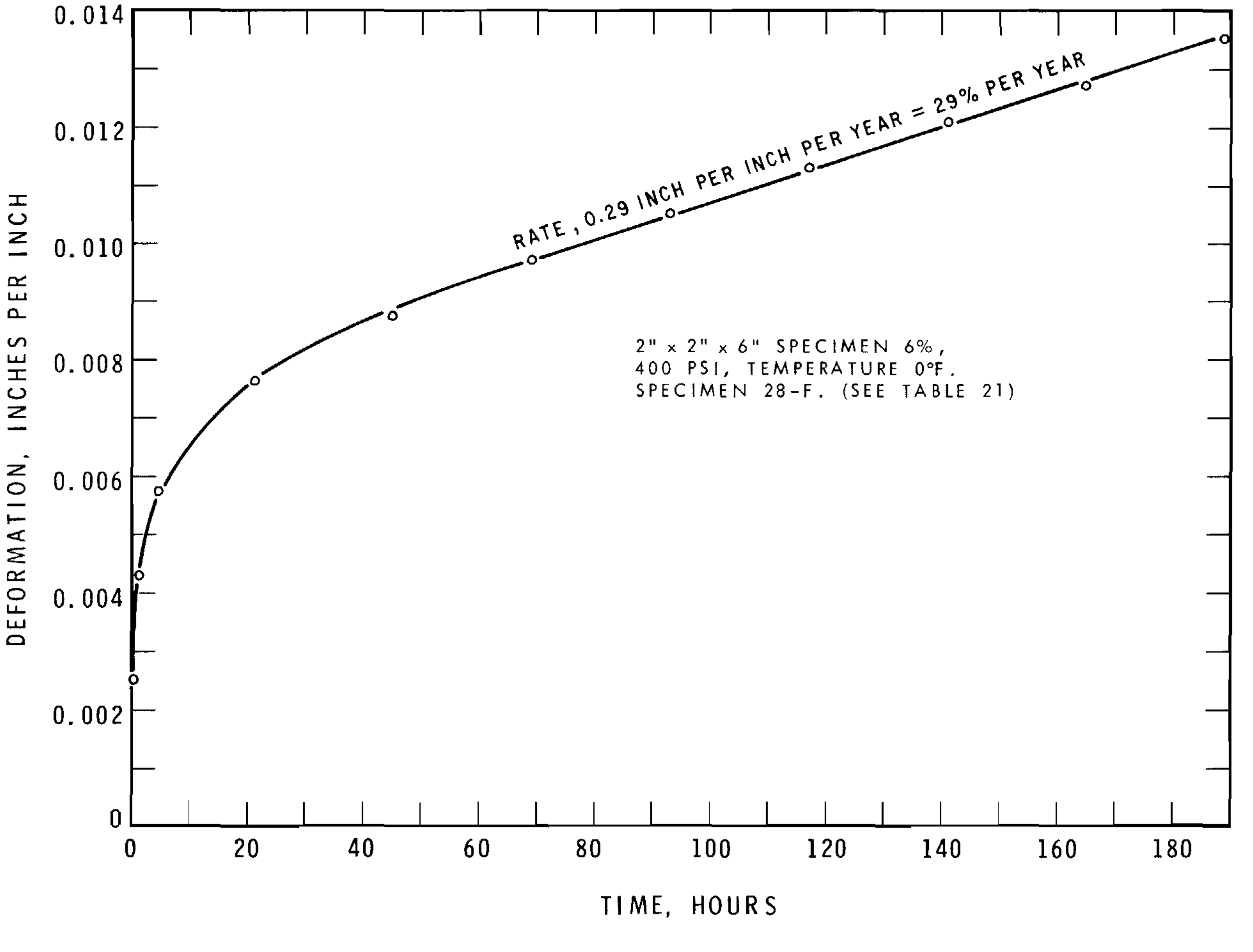

DIAGRAM 2 PLASTIC FLOW - COMPRESSION

BR 4942 - 2

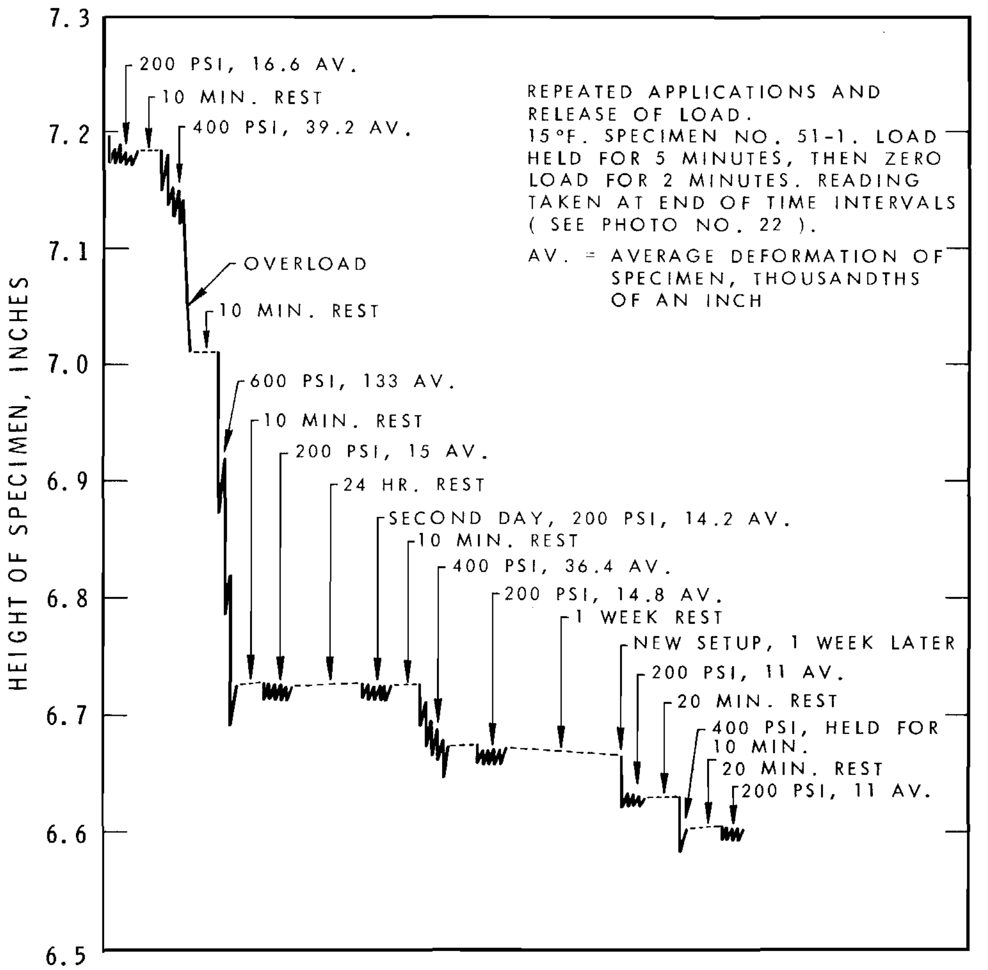

DIAGRAM 3 PLASTIC - COMPRESSION

BR 4942 - 3

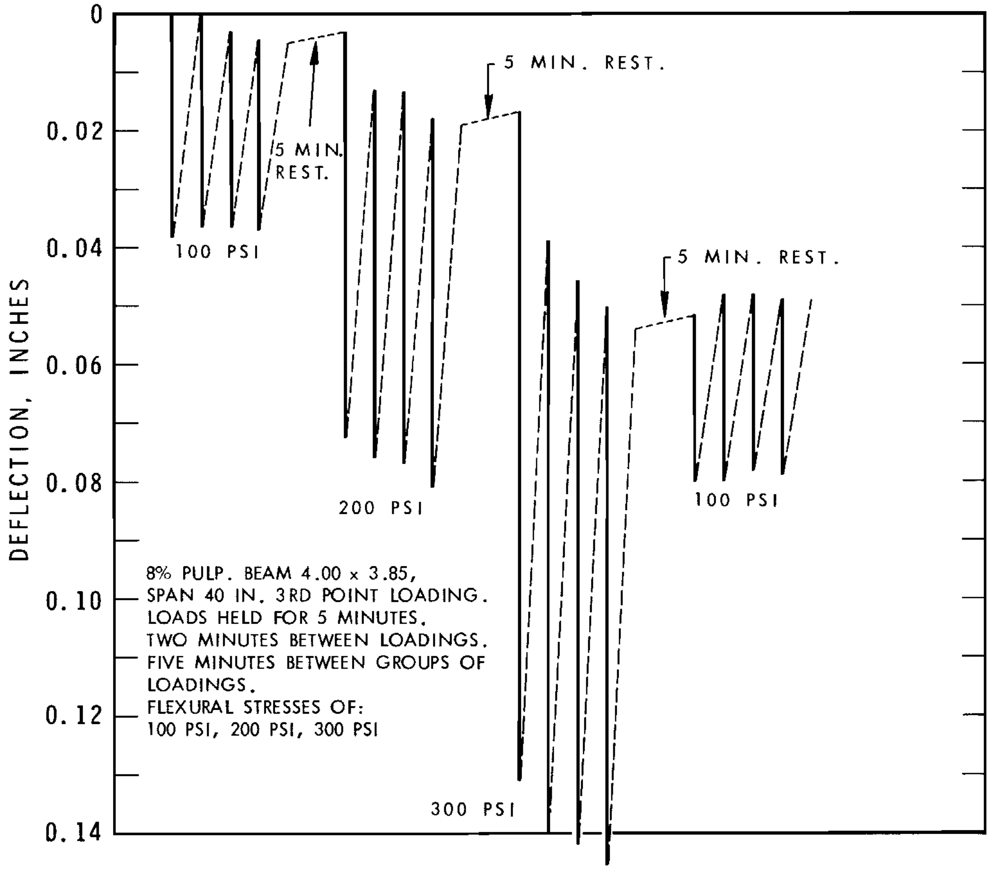

DIAGRAM 4

PLASTIC FLOW AND DEFLECTION OF BEAM UNDER REPEATED LOADINGS

BR 4942-4

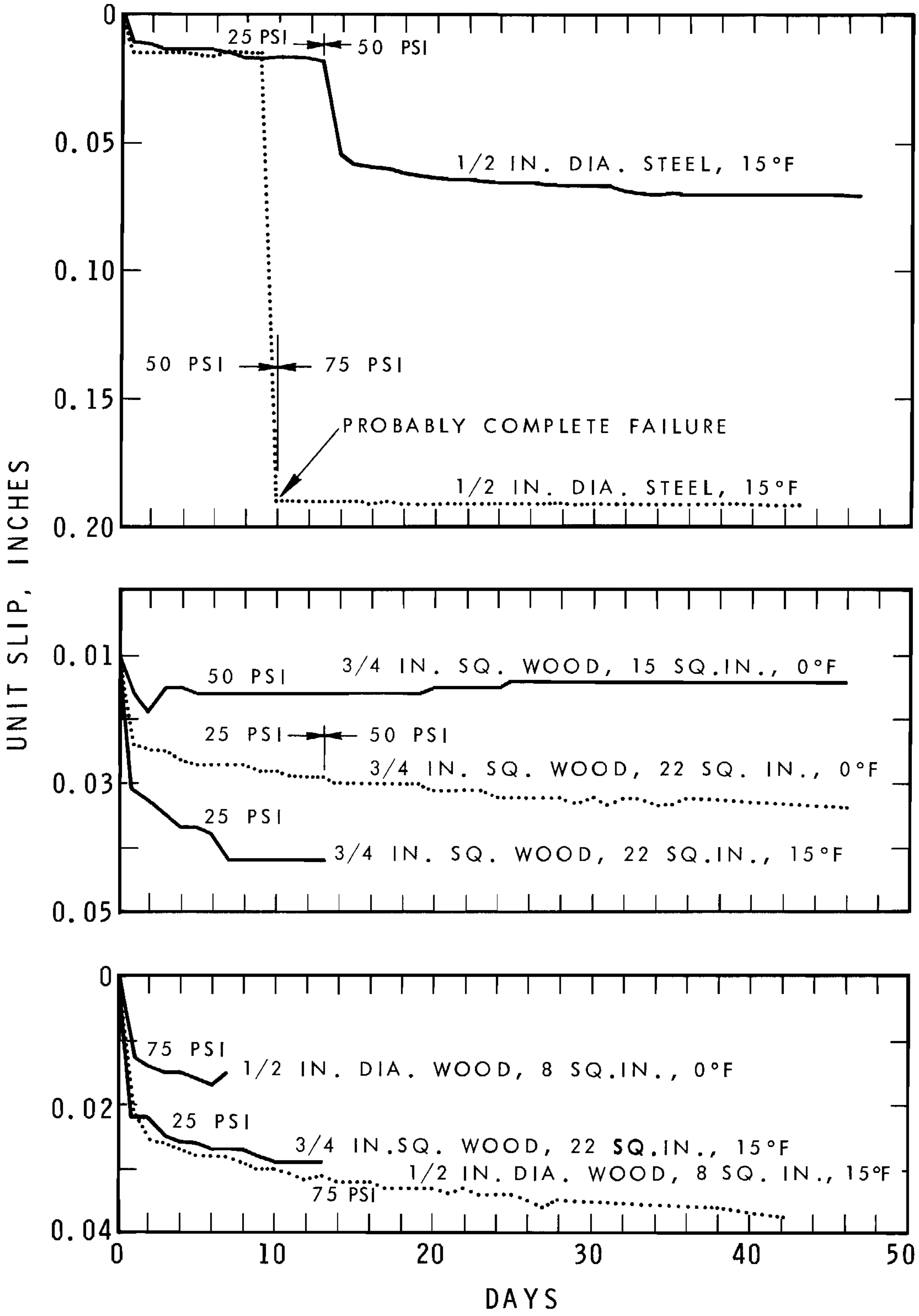

DIAGRAM 5

SLIP OF REINFORCING BARS UNDER SUSTAINED LOADS, 6% PULP

BR 4942 – 5

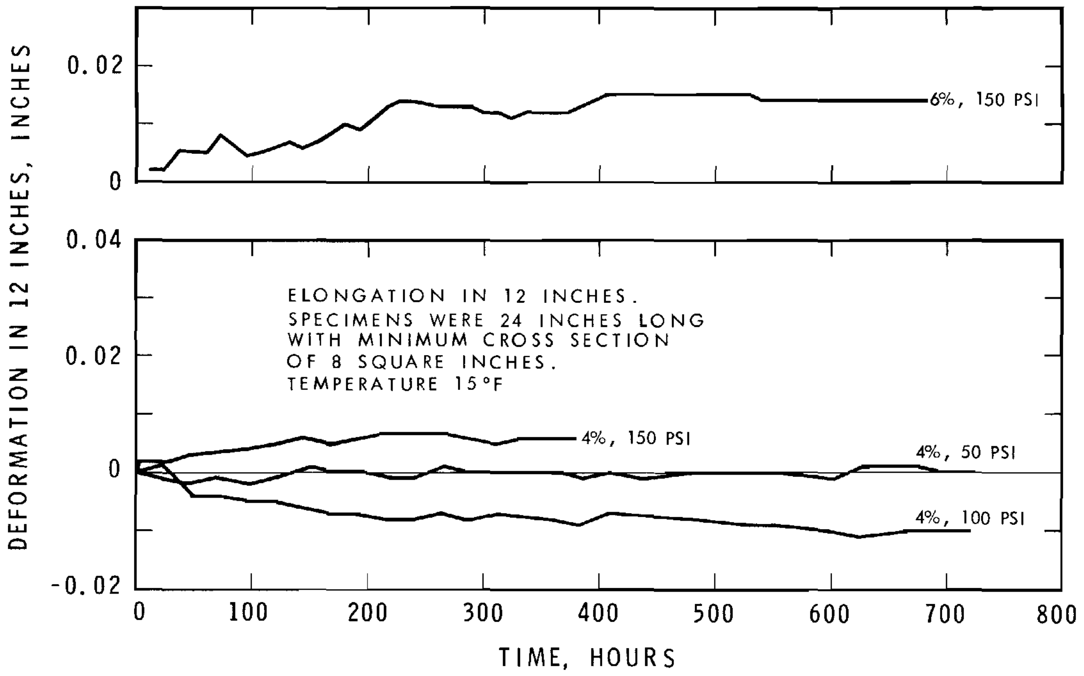

DIAGRAM 6 PLASTIC FLOW IN TENSION

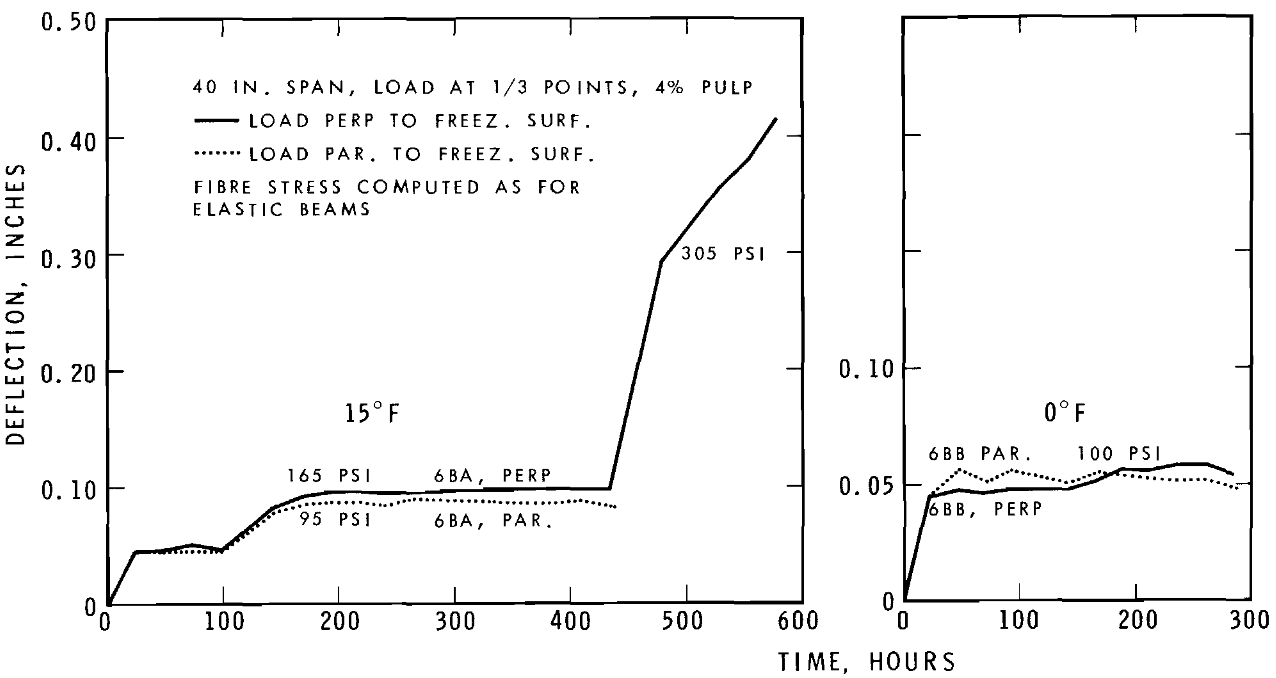

DIAGRAM 7

DEFLECTION OF 4" x 4" x 43" BEAMS, SUSTAINED LOADING

BR 4942-7

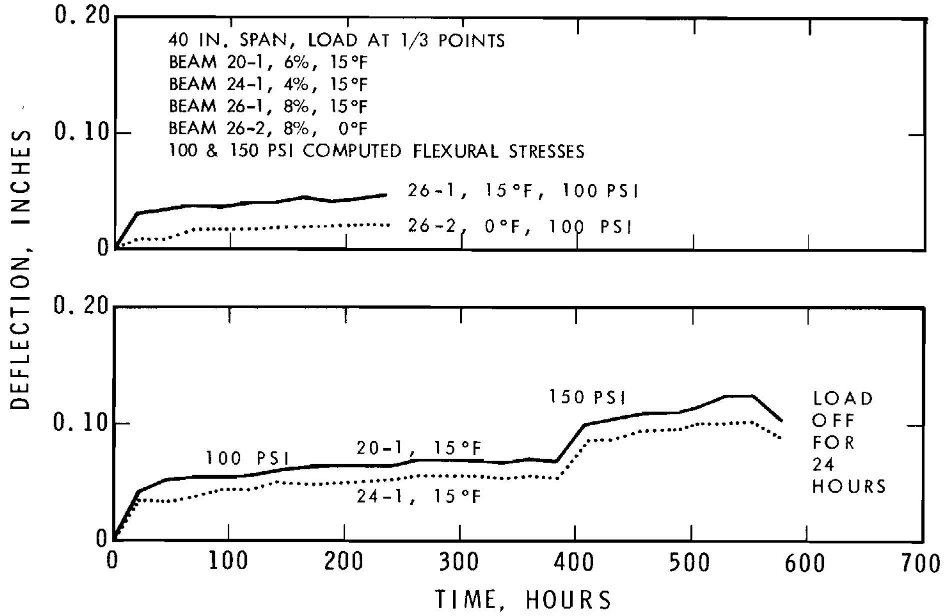

DIAGRAM 8

DEFLECTION OF 4" x 4" x 43" BEAMS, SUSTAINED LOADING

BR 4942 - 8

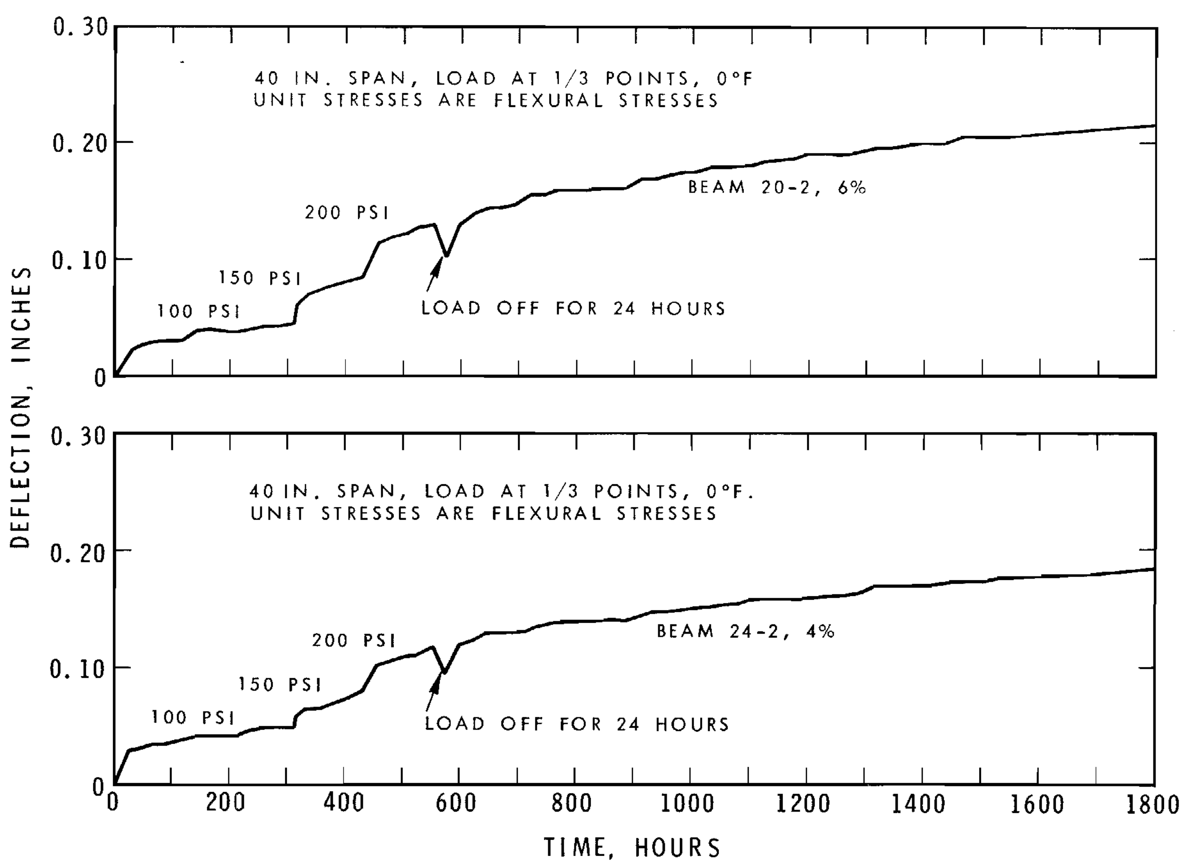

DIAGRAM 9

DEFLECTION OF 4" x 4" x 43" BEAMS, SUSTAINED LOADING

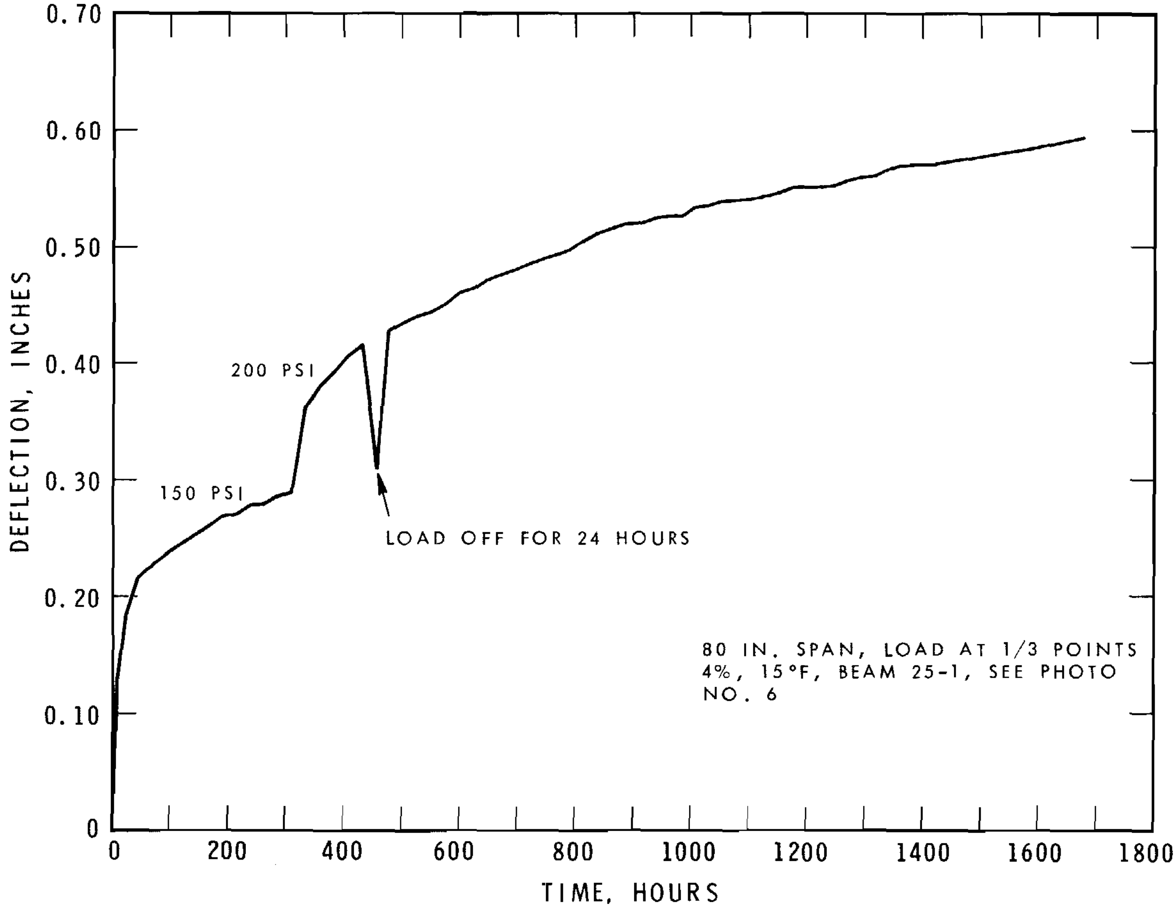

DIAGRAM 10

DEFLECTION OF 4" x 8" x 85" BEAM, SUSTAINED LOADING

BR 4942 -10

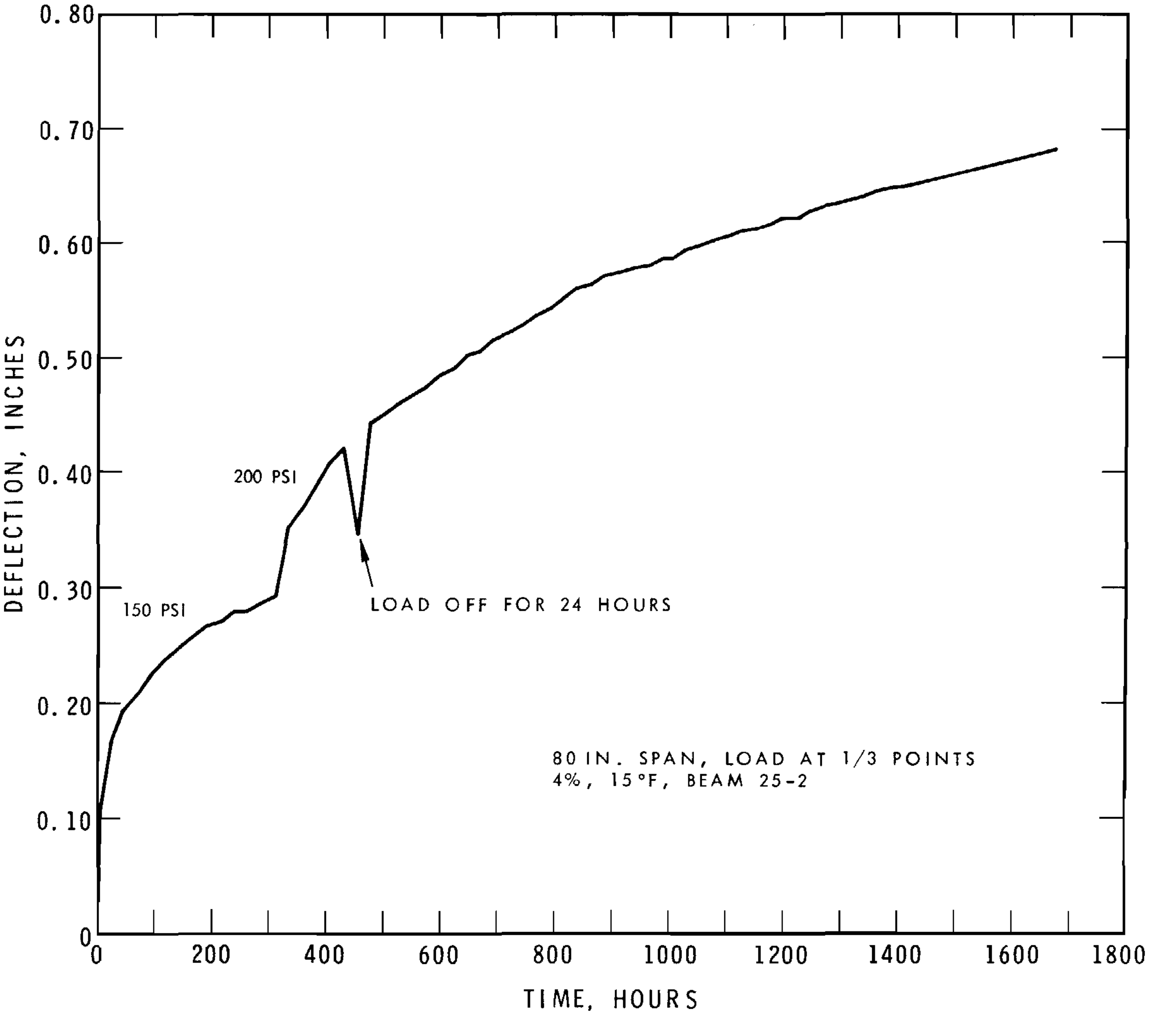

DIAGRAM 11

DEFLECTION OF 4" x 8" x 85" BEAM, SUSTAINED LOADING

BR 4942-11

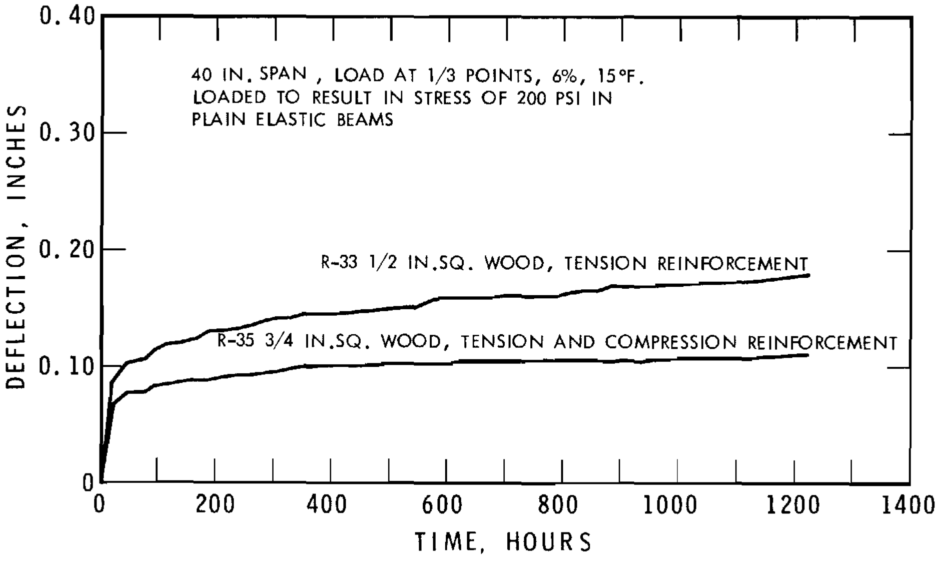

DIAGRAM 12

DEFLECTION OF 4" x 4" x 43" REINFORCED PULP BEAMS, SUSTAINED LOADING

8R 4942 -12

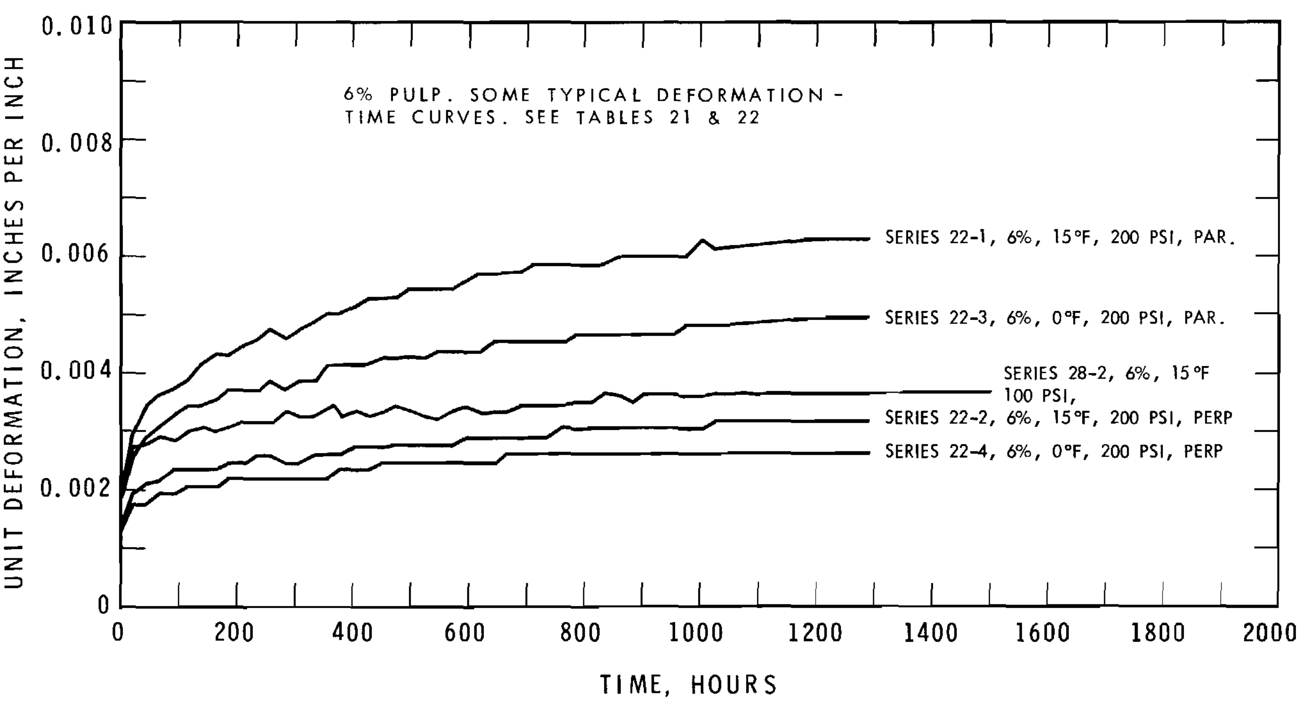

DIAGRAM 13 PLASTIC FLOW IN COMPRESSION

8R 4942 - 13

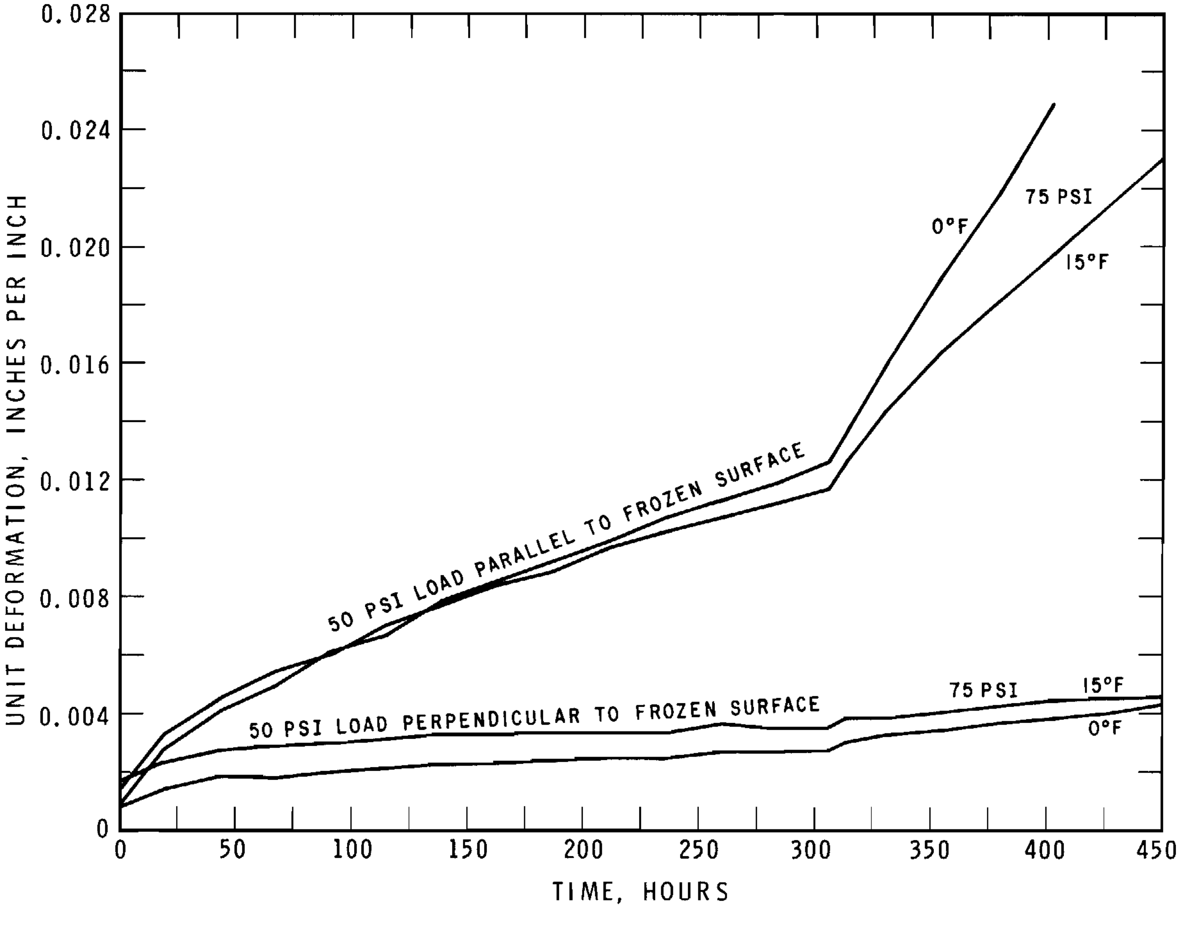

DIAGRAM 14 COMPRESSIVE CREEP FLOW OF RIVER ICE

8R 4942-14

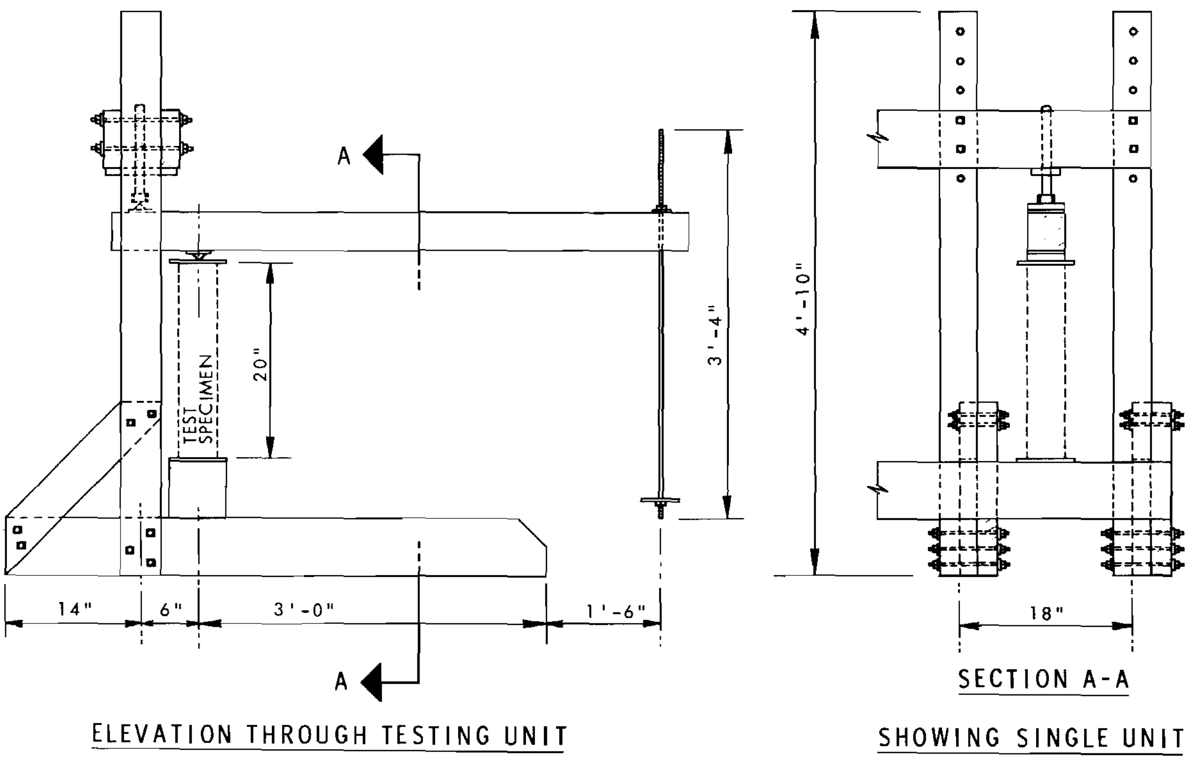

DIAGRAM 15

WOODEN LOADING FRAMES FOR SUSTAINED LOADING OR PLASTIC FLOW TEST IN COMPRESSION AND FLEXURE

8R 4942 -15