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Flexural Properties of Snow and Snow-Ice

by

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PREFACE

This report was prepared by Mr. S. Russell Stearns, Civil Engineering Department, Dartmouth College, for the Applied Research Branch. The work was done under contract DA-11-190-ENG-32.

This report has been reviewed and approved for publication by Headquarters, U. S. Army Materiel Command.

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SUMMARY

One testing objective was to determine if small, select samples of natural snow-ice, tested in bending, would provide consistent and higher values for the flexural strength and modulus of elasticity. Another objective was to investigate the surface bearing properties of snow-ice layers, formed during witner on lakes or rivers, which are often separated from clear ice by an interlayer of slush or water. Samples of this type of snow-ice were obtained from Post Pond in New Hampshire. The other forms of ice-cap snow, natural snow (top and 15-ft depth), and high-density snow were tested during two summers on the Greenland ice cap. Densities in all cases were obtained by cutting a cube of snow from the sample beam adjacent to the break. The apparatus used in testing the Post Pond snow-ice beams was a modification of a Soiltest hand-operated press with a 0- to 5000-lb wooden, three-point load device.

Dense snow-ice at +5° had high flexural strength (avg. 347.5 psi) and a high modulus of elasticity (avg. 6.08×10^5 psi), probably the result of a large, interlocking crystal structure. The apparent relationship between modulus of elasticity and density of snow-ice is affected by the rate of loading and temperature. There appears to be a relationship between density and flexural strength for snow, snow-ice, and high-density snow in the natural undisturbed state; but processing, including snow compaction, lowers the tensile strength at early ages. The formulas used in computations are given and test results are tabulated and summarized.

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INTRODUCTION

A considerable quantity of data has been published in the last decade on the strength of snow and ice. These publications have provided information on the composition, strength, and stress-strain relationships of sea ice, fresh water ice, snow-ice, and snow of various densities (see References). Direct compression and tension, ring and beam tension, and torsional shear tests have been conducted in the laboratory and in the field, on large and small samples.

The results of these tests have usually shown considerable variation, and much effort has been applied in an attempt to relate stress-strain and ultimate strength properties to temperature, density, rate of loading, and size and composition of the material tested. There is some similarity between this situation and that which exists in the determination of the properties of wood to be used as structural timber. In this latter case small, select samples are used (ASTM, 1961), and a factor of safety is introduced in the design to take into account the actual differences and weaknesses in the larger, structural element. Similar values for natural snow-ice are needed, and one objective of these tests was to determine if small, select samples of natural snow-ice, tested in bending, would provide consistent and higher values for the flexural strength and modulus of elasticity. As evidenced by previous tests, the presence of planes and points of weakness in a sample beam will reduce the strength and cause erratic results. It is expected that small select samples of snow-ice, with cracks and holes eliminated, will lead to more consistent results for the actual internal structure and distribution of grains and voids found particularly in snow-ice (Butkovich, 1958).

In many parts of the polar and sub-polar areas, snow-ice is formed on lakes and rivers during the winter. This layer of ice, often separated from the clear ice by an interlayer of slush or water, may provide the bearing surface for aircraft landings and sometimes for surface vehicles. Investigation of the properties of this layer forms a second objective of this report. Samples of this type of snow-ice were obtained from Post Pond in Lyme, New Hampshire.

Other forms of snow and snow-ice were observed and tested during two summers at Site 2 on the Greenland Ice Cap. Beam tests were run on samples of natural ice-cap snow, cut from the top 4 ft, from 12 to 15 ft, and from a 100-ft deep pit (Butkovich, 1956). In addition, samples of reworked snow were cut from an experimental, compacted snow runway, and from snow deposited by a Peter snow miller (Stearns, 1959; Wuori, 1960).

These tests were performed to see if there is any correlation between the flexural strength and snow density, and if there is any effect on flexural strength due to reworking or processing the snow.

DESCRIPTION OF SAMPLES

The six types of snow-ice and snow tested in flexure will be referred to as:

1. Post Pond snow-ice
2. Ice-Cap natural snow—top surface
3. Ice-Cap natural snow—15-ft depth
4. High-density snow
5. Processed snow—compacted runway
6. Processed snow—Peter snow.

Densities in all cases were obtained by carefully cutting a cube of snow from the beam adjacent to the break. This cube was measured and weighed in air.

Post Pond snow-ice

This snow-ice was cut from Post Pond, Lyme, New Hampshire, at a spot about 200 ft offshore. The temperature at the time of cutting was between 20 and 25F. The ice, cut in 12 x 30 x 10 in. blocks, was stored in a frozen food locker at -15C (+5F).

The ice profile at the time of cutting, with some variation in thicknesses, was as follows:

Snow	8 in.
Snow-ice, soft or crust	4 in.
Snow-ice, dense	6 in.
Water and slush	4 in.
Clear ice	10 in.

During storage, the ice cooled uniformly to +5F with some cracking of the blocks resulting.

The beams, 1 in. high, 2 in. wide, and 12 in. long, were cut horizontally from the 6-in. layer of dense snow-ice, with a band saw and guide fence. Care was exercised to cut straight, parallel-sided beams of ice free of cracks. The cross section was measured to the nearest sixteenth of an inch giving a possible error of .031 in. This is a 3% error in the 1-in. height, and 1.5% in the 2-in. width. Since the height is squared in the determination of the flexural strength, this might result in a 6% error. The beams were broken the day they were cut.

The density samples were also measured to 1/16 in. For a 1 x 2 x 3 in. cube the possible error would be 5.5%. These errors are greater than those for the larger snow beams tested in the field in Greenland, but it is felt that the better beam preparation somewhat compensates for this deficiency.

Ice-Cap snow

The field samples were cut with a handsaw with an effort made to obtain parallel-sided beams. The bearing surfaces were shaved to reduce torsional loading. These beams were all larger than the Post Pond snow-ice beams because of lower strength and density. The high-density snow and Peter snow beams were quite homogeneous, and could have been smaller. However, the larger beam cut from the compacted snow runway provided a more representative sample of the random snow and ice skeleton found there.

The beam cross section was measured to the nearest 0.1 in. and the beam span of 24 in. was accurately set. There was never more than 1 in. overhang. The samples for density were recut into cubes at the break and measured to the nearest 0.1 cm. These cubes ranged in volume from 500 to 1500 cm^3 for the Peter snow and runway snow, and the high-density snow cubes were about 250 cm^3.

Natural snow, top and 15-ft depth. These beams were cut horizontally from the side of a 20-ft deep trench cut by the Peter snow miller. One series of 18 beams was cut from the top surface from 0-4 ft, and a second series of 62 beams was cut from 12-15 ft. Since this snow is naturally stratified, the beams were selected to be as homogeneous as possible and representative of various densities from 0.35 to 0.52 g/cm^3. The temperature was recorded for the center of the broken beams, and ranged from 12 to 20F, except for eight beams in the deeper series which ranged from 8 to 0F. All beams were broken in the trench immediately after cutting. Since they were handsawed, there was some variation in cross section, but each was carefully measured at the break point. They averaged 3 x 4 x 26 in.

High-density snow. These beams were cut horizontally from the bottom of a 100-ft deep pit at Site 2. The sampling is from the upper layer of the densified ice cap in a no-melt zone, and the snow selected is quite homogeneous with a density between 0.66 and 0.68 g/cm^3. The temperature in the deep pit was about -12F. The snow beams were removed to a snow lab, under the surface of the ice cap, where they remained at 6F for at least 24 hr before testing. The sample beams were of variable cross section, but averaged 2 x 2 x 26 in. Each was measured carefully at the break point.

Peter snow — processed. These beams were cut horizontally from snow deposited by the Peter snow miller, 16 from blown snow adjacent to a trench cut and 7 from snow backfilled on the first experimental trench arch at Site 2. Tests were run outside at the existing ambient temperature 20 to 22F. The beams were cut to approximately 2 x 4 x 26 in. but the cross section varied considerably. Each was measured carefully at the break point. The Peter snow was between 1 and 4 weeks old so initial set had occurred.

Compacted-snow runway. These beams were cut horizontally from the experimental, compacted-snow airstrip at Site 2. The runway was built utilizing equipment which pulverized and heated snow, then backgraded and rolled it into a thickness of about 3 ft. Since the heating was not uniform and mixing not complete, ice lenses, chunks, and general nonhomogeneity resulted. The beams sometimes contained holes, cracks, and icy or granular pockets, and over-all results reflect these discontinuities (see App. B). Beams were approximately 3 x 5 x 26 in., but varied considerably in cross section. Each was measured carefully at the break point. The tests were run at the airstrip with the beam temperature ranging from 20 to 27F.

APPARATUS

Post Pond snow-ice

The laboratory apparatus used in testing the Post Pond snow-ice beams was a modification of a Soiltest hand-operated press with a 0-500 lb proving ring.

The dial gage in the proving ring is read to .0001 in. and the dial gage used to measure the center deflection is read to .001 in. The supporting steel channel is 2 x 1 x $\frac{1}{4}$ in., lying flat. The bearing points are $\frac{1}{2}$-in. diam round wooden dowels mounted on the flat face of the channel exactly 12 in. apart.

The upper load was applied through a solid steel bar to which $\frac{1}{2}$-in. diam round dowels were accurately attached, 4 in. apart. A thin, hard, cardboard shim was used where necessary to assure simultaneous, parallel load contact with the surface of the test beam. In most cases the careful preparation of the beam with minor shaving at the contact points provided parallel load surfaces, thus eliminating torsion.

Deflection of the steel channel and steel bar were found to be 0.001 in. for a load of 100 lb. This is not significant for the range of loads and deflections measured. The resistance of the deflection gage was also found to be insignificant.

The rate of stress application was maintained reasonably constant by the manual operation of the screw jack. For the 1 x 2 x 12-in. samples tested, load was applied at the rate of five divisions of the load dial per second which is equivalent to 0.7 kg/cm^2-sec (Butkovich, 1958). The average rate of deflection of the center of the beam was 0.033 in./min (Table II).

Ice-Cap snow

The field apparatus used in Greenland consisted of a wooden, three-point load device (Fig. 1) (Frankenstein, 1959). The distance, $\underline{a}$, from the support to the fracture was measured for each beam in order to compute actual stress at the failure point.

No attempt was made to measure deflections, and only the load at failure was recorded. The weight of the beam and the weight of the 2 x 4-in lever were taken into account in the computations.

The test was run very rapidly, taking no more than 10 sec. Except for the Peter snow beams, temperature was determined by inserting a thermometer into the fractured end of the beam.

TEST RESULTS

Flexural strength

The flexural strength was determined for all beams. A summary of the results is shown in Table I, and full data are included in Appendix B. Formulas used are given

Table I. Average flexural strength and modulus of elasticity.

Sample	Avg. density (g/cm^3)	Avg. fluxural strength (psi)	Avg. modulus of elasticity (psi)
Post Pond	.894	347.5	6.08×10^5
Ice Cap-top	.403	7.5	—
Ice Cap-15 ft	.465	32.9	—
Ice Cap-100 ft	.67	169.0	—
Compacted runway	.578	35.5	—
Peter snow	.565	21.5	—

Table II. Deflection, Post Pond snow-ice.

Beam	Time (sec)	Deflection (in.)	Rate (in./min)
S1	28	.013	.028
S2	43	.031	.043
S3	35	.018	.031
S4	31	.018	.035
S5	32	.020	.037
S6	30	.013	.026
S7	32	.018	.034
S8	35	.019	.033
S9	39	.018	.028
S10	19	.009	.028
S11	28	.020	.043
S12	48	.023	.029
S13	51	.029	.034
S14	35	.022	.038
S15	45	.024	.032
S16	47	.029	.037

Avg. rate = .0335 in./min.

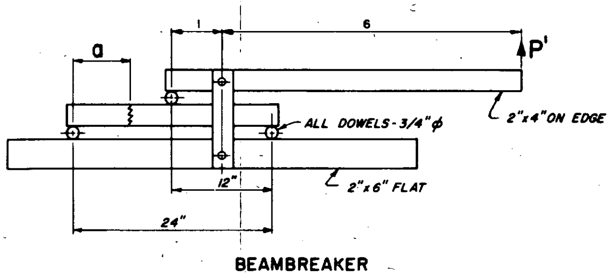

Figure 1. Test apparatus for field tests.

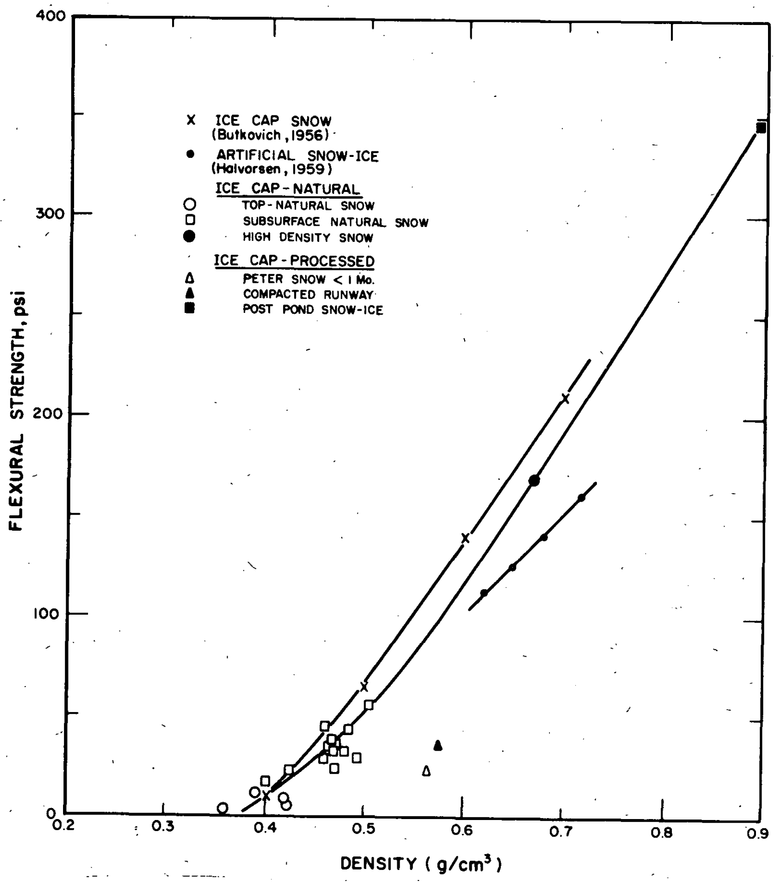

Figure 2. Flexural strength vs density for various types of snow and snow-ice.

in Appendix A. Figure 2 shows the variation of flexural strength with density. There is a good correlation with the curve obtained from ring tensile tests performed on Greenland Ice Cap snow by Butkovich (1956, p. 4) despite the fact that they are the results of two different tensile tests. Also, the flexural strength of natural snow beams follows a consistent trend from low-density surface snow, through high-density, deeper ice-cap snow, to natural snow-ice on a New Hampshire lake. The scatter of the values at low density is to be expected from the variability in structure including horizontal, strengthening crust and ice strata.

It is also of considerable interest to note that the beams from the two processed snow deposits, Peter snow and compacted runway, showed lower flexural strength than the curve. Results for artificial snow-ice (Halvorsen, 1959) plotted for comparison appear on the weaker side also, although at a different slope. This is not the case with compressive strength, and may be due to the younger age of the processed snow. The intergranular bond necessary for tensile strength has not had sufficient time to develop to the degree that it has in the older, natural snow. This bond is not as critical in the case of direct compression, and therefore the reduction is not a factor in an arch under compression; it could be critical for snow structures using beam loading. One-month old Peter snow in a larger cantilever beam failed at $\sigma = 2.33$ kg/cm^2 = 33.1 psi, or slightly higher (Stearns, 1959).

Hitch (1959) reports the flexural strength of clear lake ice from Lake Superior as 173 psi average, and 225 psi maximum. He reports other values including Brown's results for northern Lake Michigan ice: 311 psi and 306 psi maximum. Since all these results are for tests at temperatures from +15F to +29F, it would be expected that the Post Pond results at +5F would be higher. Nevertheless, it is apparent that the dense snow-ice from Post Pond is a very strong flexural material. Its high density plus interlocking structure gave an average stress of 347.5 psi which makes it as good a material for landing aircraft as clear ice for comparable thicknesses, as long as no water or slush layer is present between the snow-ice and clear ice. It must be remembered, however, that these tests were performed on select small beams which give higher results for strength. Therefore, a larger factor of safety must be introduced for full-scale field loading. Frankenstein (1959) provides some comparison of small beam tests with larger, in situ tests, and points out the higher values from small tests.

Modulus of elasticity

The modulus of elasticity was found only for the Post Pond snow-ice. The deflection of the center of each beam was measured (Table II) and the load-deformation curves plotted (Fig. 4). The rate of loading averaged 0.7 kg/cm², and the average deflection of the midpoint of the beam was 0.0335 in./min. The values for the modulus of elasticity show considerable variation (see Fig. B1), but the average value of 6.08 x 10^5 psi agrees well with results obtained by other investigators (Fig. 3). Hitch reports that dense snow-ice with large crystals gives a higher value of E. Brill and Camp (1961) give an average value of E = 8.12 x 10^5 psi for artificial snow-ice, density = 0.886 g/cm³. The test was in direct tension, and the sample ~~was~~ smaller. The modulus of elasticity plotted against the flexural strength shows no trend (Fig. B2).

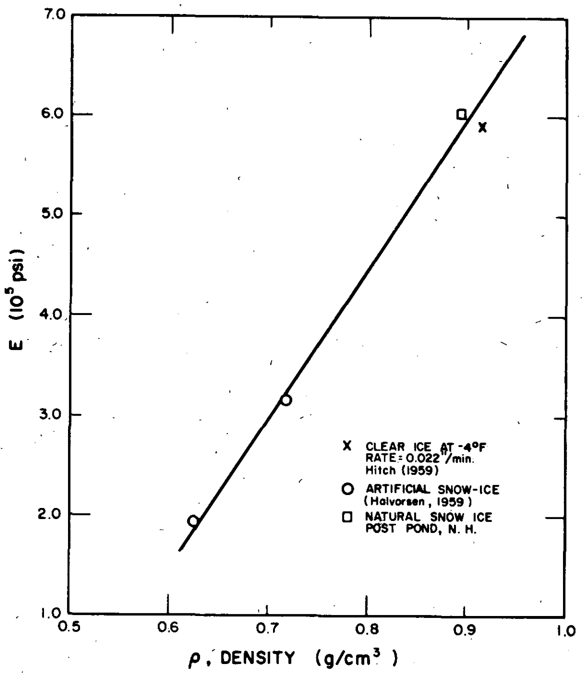

Figure 3. Modulus of elasticity vs density, snow-ice.

Sources of error

There are three major sources of error. First, if the top and bottom of the beams are not parallel, and if the application of load is not uniform across the full width of the beam, torsion will result and the flexural strength will be lower than actual. Although care was exercised to prevent torsion, some of the erratic nature of the results may have been due to this. It is recommended that one end of the load and support application be through a thin metal plate resting on a sphere. This will allow the plane of load application to orient itself parallel to the face of the beam.

Second, there may be some crushing of snow-ice beams under the points of load, which will cause deflection readings to be high. This would result in lower values of the modulus of elasticity. It is doubtful that this occurred with the dense, Post Pond snow-ice. If deflections are measured for low-density snow beams, this crushing should be prevented.

Thirdly, measurement of volume and cross section is critical for density and flexural strength. If volume and weight in air are used for density, extra care must be taken in measurement. The impossibly high density values for some Post Pond snow-ice may be due to inaccurate volume determination. This error may also be in some of the lower density results though not as apparent. It is recommended that an immersion or displacement method be used for volume determination.

The value for the flexural strength depends upon the square of the beam thickness, and the modulus of elasticity depends upon the cube of the thickness. Therefore, these measurements must be made with care.

CONCLUSIONS

Dense snow-ice has high flexural strength and a high modulus of elasticity. This is probably a result of its large, interlocking crystal structure.

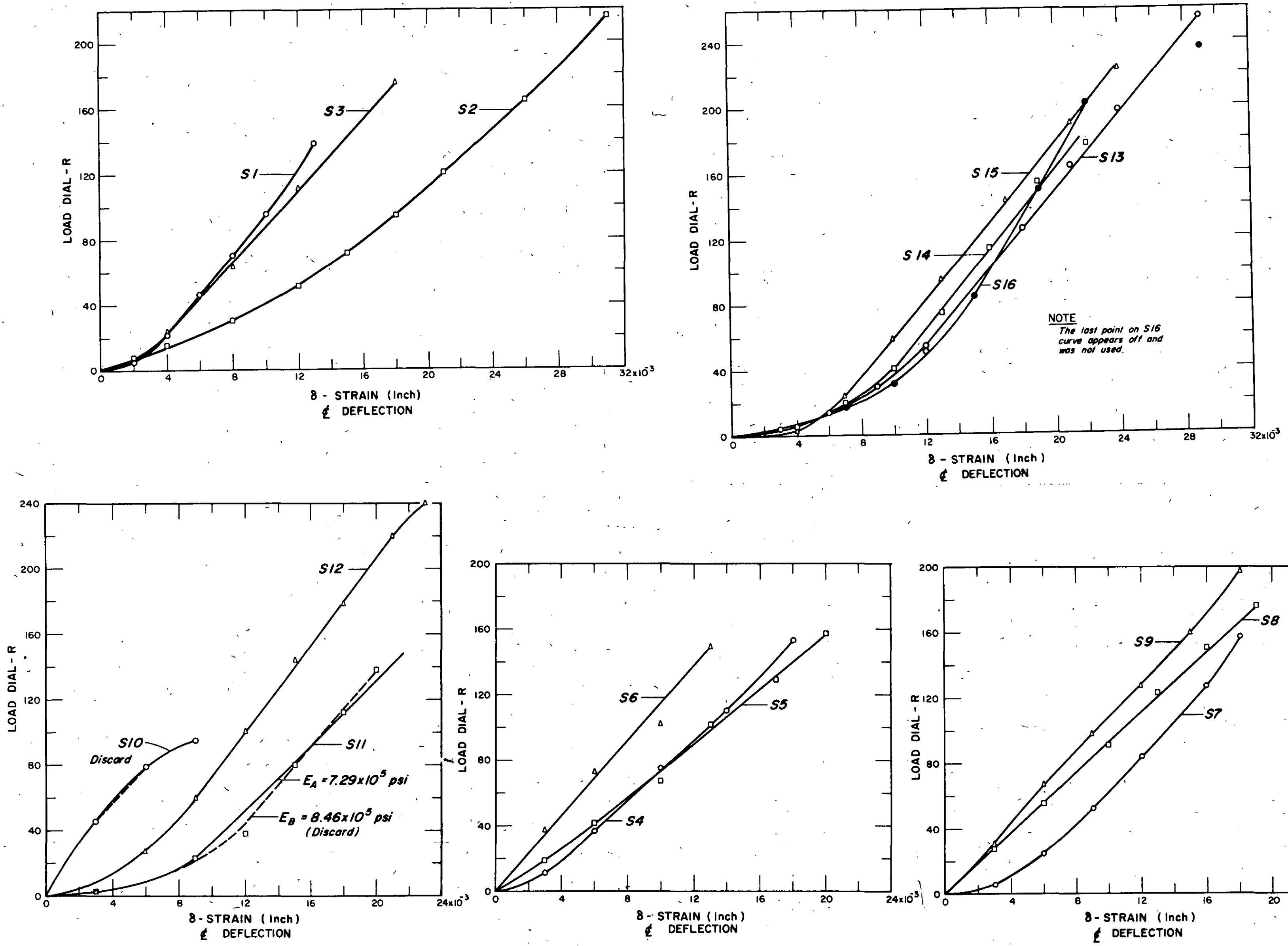

Figure 4. Load vs deformation, Post Pond snow-ice. δ avg = 0.033 in./min. P (lb) = .325 R. Proving ring 1791.

There appears to be a relationship between modulus of elasticity and density of snow-ice. The rate of loading and the temperature affect these results, however.

There appears to be a relationship between density and flexural strength for snow, snow-ice, and high-density snow in the natural undisturbed state, but processing, including compaction of the snow, appears to lower the tensile strength at early ages.

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APPENDIX A: FORMULAS

Post Pond snow-ice

P = load in pounds from load dial
R = load dial reading = $P/.325$
δ = deflection of the center of the beam
b = width of beam
h = height of beam, $c = \frac{h}{2}$
I = moment of inertia $= \frac{bh^3}{12}$
ℓ = length = 12 in.
a = distance to breaking point for center loading

Flexural strength, σ

$$\sigma = \frac{Mc}{I} = \frac{M}{Z} = \frac{6M}{bh^2}$$

$$M = \frac{P}{2}(4) = 2P$$

$$\sigma = \frac{6(2P)}{bh^2} = \frac{12P}{bh^2} = \frac{3.9R}{bh^2}$$

Modulus of elasticity, E

$$\delta = \frac{\left(\frac{P}{2} \cdot a\right)}{24\ EI}\ (3\ell^2 - 4a^2)$$

$$E = \frac{119.6}{bh^3} \times \frac{(R)}{\delta}$$

$\frac{R}{\delta}$ = slope of the deflection curve, Figure 4.

Ice-Cap snow

Flexural strength - center loading

The weight of the beam is included.

Concentrated load P

$$M_1 = \frac{P}{2}(a)$$

Weight of beam - neglect small overhang.

$$M_2 = \frac{\ell bh\rho}{2}(a) - abh\ \rho\frac{a}{2} = \frac{bh\rho a}{2}(\ell - a)$$

$$M = \frac{Pa}{2} + \frac{a}{2}\ bh\rho\ (\ell - a)$$

$$\text{Stress, } \sigma = \frac{Mc}{I} = \frac{2M}{bh^2}$$

$$= \frac{3a}{h}\left(\frac{P}{bh} + \rho\ell - \rho a\right)$$

APPENDIX B: DATA

Table B1. Post Pond snow-ice.

Beam	Density ρ (g/cm^3)	Height h (in.)	Width b (in.)	Load P (lb)	Flexural Strength, σ (psi)	Modulus of elasticity, Ex10^5 (psi)
S1	0.96	1.0	2.0	678.6	339.3	7.28
S2	0.97	1.0	2.0	885.3	442.7	5.24
S3	0.91	1.0	2.0	682.5	341.3	6.50
S4	0.89	15/16	1 15/16	596.7	350.4	7.30
S5	0.91	15/16	2.0	612.3	348.3	6.01
S6	0.90	1.0	2.0	616.2	308.1	6.86
S7	0.90	1 1/16	2.0	612.3	271.2	5.34
S8	0.94	1.0	1 15/16	686.4	354.2	5.71
S9	0.85	1 1/16	2.0	768.3	340.3	5.15
S10	0.90	1 1/8	1 5/8	370.5	180.1	5.69
S11	0.96	1.0	1 5/8	538.2	331.2	7.29*
S12	0.92	1 1/16	2.0	936.0	414.5	6.64
S13	0.88	1 1/8	2 1/8	1053.0	391.6	4.65
S14	0.87	1 1/8	2 1/16	690.3	264.5	4.93
S15	0.91	1 1/16	2 1/16	869.7	373.6	5.77
S16	0.84	1 1/8	2 1/8	916.5	340.8	6.60

ℓ = 24 inches for all beams.

*Two determinations of E were made. The other value, 8.46 x 10^{-5} psi, was discarded.

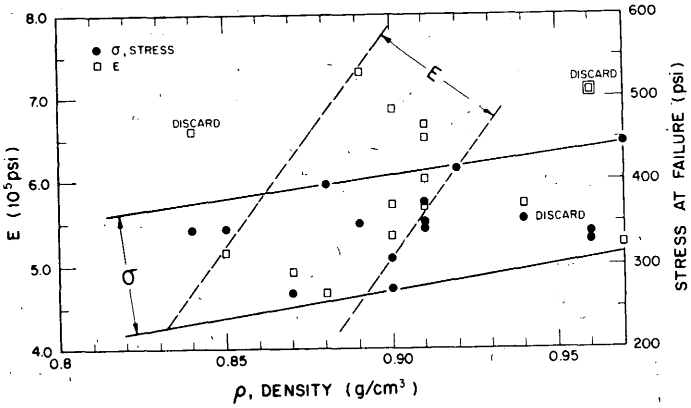

Figure B1. Modulus of elasticity vs density Post Pond snow-ice. (1957-58)

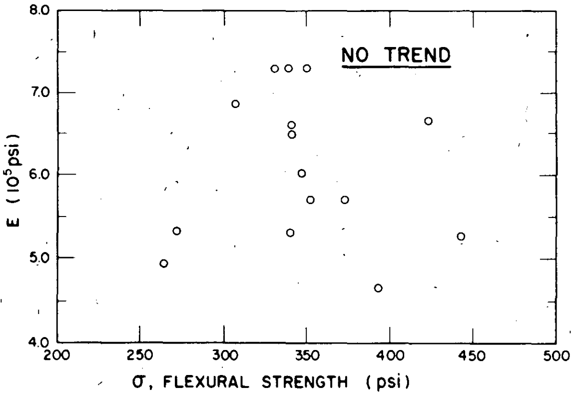

Figure B2. Modulus of elasticity vs flexural strength, Post Pond snow-ice. (1957-58)

Table B2. Ice-cap snow-natural, 1-3 ft depth (ℓ = 24 inches for all beams.)

Beam	Density ρ (g/cm^3)	Height h (in.)	Width b (in.)	Load P (lb)	Max stress at center, σ (psi)	Break off center (in.)	Strength at break (psi)
e-1	0.359	4.25	3.0	6.0		7.5	2.30
2	0.359	3.7	3.3	4.5	4.84		
3	0.359	3.7	3.3	4.5			
a-2	0.391	3.36	3.36	10.5	11.8		
3	0.391	3.24	3.36	10.5	12.6		
4	0.391	3.24	3.36	6.0		1.0	7.5
5	0.391	3.36	3.0	13.5	16.1		
6	0.391	3.12	3.48	4.5	6.8		
b-1	0.424	3.84	3.60	10.5	8.9		
2	0.424	3.84	3.12	4.5		1.0	4.7
4	0.424	4.08	3.00	1.5	2.7		
6	0.424	3.84	3.24	3.0		6.5	2.3
c-1	0.420	3.96	3.24	12.0	10.2		
2		3.84	3.12	9.0	8.8		
3		3.72	3.48	7.5		3.0	5.6
4		3.48	3.24	6.0	7.4		
5		3.48	3.48	10.5		2.0	9.3
6		3.48	3.60	7.5		1.0	7.6

Table B3. Ice-cap snow-natural, 12-15 ft depth.

a-1	0.401	3.7	3.5	20.25	16.8		
2	0.408	Broke					
3	0.408	3.8	2.8	15.75	15.7		
4	0.408	3.7	2.7	14.14	15.6		
5	0.408	Broke					
b-1	0.470	3.7	3.2	27.75	24.8		
2	0.465	3.7	2.8	26.25	26.9		
3	0.465	3.6	2.8	23.25		1.0	21.3
4	0.465	3.9	2.6	23.25	23.1		
5	0.384	3.7	3.4	24.75	22.4		
c-1	0.457	3.9	3.5	45.75	32.7		
2	0.460	3.8	3.1	32.25	27.9		
3	0.460	3.8	2.4	26.25	29.3		
4	0.460	3.7	2.7	29.25	30.4		
5	0.462	3.6	3.4	38.25		2.5	26.8
d-1	0.462	3.4	3.4	44.25	42.5		
2	0.462	3.6	3.1	51.75		1.0	44.9
3	0.462	3.7	2.9	50.25	47.6		
4	0.462	3.8	2.8	51.75		1.0	44.3
5	0.462	3.8	3.2	57.25		1.0	42.8
e-1	0.494	3.6	3.2	24.25	19.7		
2	0.494	3.5	3.1	42.75	42.6		
3	0.494	3.3	3.0	26.25	31.2		
4	0.494	3.3	2.9	21.75		1.0	24.9
5	0.494	3.1	3.1	24.75		2.0	27.4
f-1	0.469	3.7	2.6	23.25	25.6		
2	0.469	4.1	3.1	39.75	29.4		
3	0.469	3.9	2.8	38.25	34.3		
4	0.469	4.1	2.8	35.25	28.8		
5	0.469	4.2	2.7	47.25	37.7		
g-1	0.464	3.5	2.9	23.25	25.6		
2	0.464	3.5	3.0	35.25		0.5	35.3
3	0.464	3.9	2.7	38.25		1.0	32.7
4	0.464	4.1	3.0	47.25	35.5		
5	0.464	4.1	2.8	45.75	36.8		
h-1	0.474	4.5	3.5	57.75	30.9		
2	0.474	4.1	3.1	68.25	49.2		
3	0.474	4.0	2.75	48.75	41.7		
4	0.474	3.9	2.9	42.75	36.8		
5	0.474	3.9	2.9	14.25	13.5		

Table B3 (Cont'd) Ice-cap snow-natural, 12-15 ft depth

Beam	Density ρ (g/cm³)	Height h (in.)	Width b (in.)	Load P (lb)	Max stress at center, σ (psi)	Break off center (in.)	Strength at break (psi)
i-1	0.422	4.1	3.25	32.25	23.0		
2	0.422	4.1	3.25	36.75	25.9		
3	0.422	4.0	2.5	27.75		2.0	22.4
4	0.422	3.75	2.5	15.75	17.8		
5	0.422	Broke					
j-1	0.466	4.75	3.0	93.75	51.2		
2	0.466	4.5	3.0	69.75			39.7
3	0.466	4.25	3.0	62.25	43.2		
4	0.466	4.5	3.0	50.25			23.8
5	0.466	4.5	3.25	59.25			27.2
k-1	0.484	4.8	3.0	59.25		3.0	24.6
2	0.484	4.3	3.2	78.75	49.6		
3	0.484	4.3	3.3	80.25	49.2		
4	0.484	6.0	3.0	107.2	37.0		
5	0.484	4.5	3.6	102.0	52.1		
l-1	0.516	3.75	3.25	69.75	56.6		
2	0.516	4.0	3.0	75.25	58.5		
3	0.516	4.25	2.5	59.25	49.5		
4	0.516	4.0	3.1	77.25		1.0	53.5
5	0.516	4.1	3.0	77.25		1.0	52.6
m-1	0.481	4.0	3.0	42.75		1.5	29.9
2	0.481	4.0	3.0	39.75	31.7		
3	0.481	4.0	3.0	38.25		2.0	25.7
4	0.481	4.25	3.0	42.75		2.0	28.6
5	0.481	4.25	3.5	60.75	38.2		

ℓ = 24 inches for all beams.

Table B4. High-density ice-cap snow, from bottom of 100 ft deep pit. (ℓ = 24 inches for all beams.)

Beam	Density ρ (g/cm^3)	Height h (in.)	Width b (in.)	Load P (lb)	Max stress at center, σ		Break off center (in.)	Strength at break	
					(psi)	(kg/cm^3)		(psi)	(kg/cm^2)
a-1	0.673	2.48	1.73	49.50	171.0	12.0			
2	0.673	2.48	1.73	46.50	160.8	11.3			
3	0.673	2.56	1.65	48.00	164.2	11.5			
4	0.673	2.68	2.09	58.50	143.2	10.1			
5	0.673	2.76	1.93	54.00	135.1	9.5			
b-3	0.673	1.73	1.73	22.50	162.9	11.4			
4	0.673	1.615	1.77	21.00	170.4	12.0			
5	0.673	1.50	2.09	21.00			1.0	154.2	10.8
c-1	0.673	1.85	1.30	22.50	187.3	13.2			
2	0.673	1.97	1.69	30.00	170.2	12.0			
3	0.673	1.97	1.97	37.50			1.0	167.0	11.7
4	0.673	1.97	1.73	34.50			1.0	174.4	12.2
5	0.673	2.16	1.93	48.00	201.1	14.1			
d-2	0.675	1.58	1.65	21.00	190.4	13.4			
3	0.675	1.65	1.77	22.50			1.0	160.4	11.3
4	0.675	1.54	1.73	19.50	178.8	12.5			
5	0.675	1.58	2.24	24.00	161.7	11.3			
e-1	0.670	1.89	2.13	36.00	175.4	12.3			
2	0.670	2.16	2.13	48.00	178.5	12.5			
3	0.670	2.16	2.09	49.50				173.0	12.1
4	0.670	1.89	1.85	36.00	201.2	14.1			
5	0.670	1.38	1.97	21.00			2.0	192.2	13.5
f-1	0.664	2.36	2.08	48.0			1.0	141.1	9.92
2	0.664	1.81	2.01	28.5	162.2	11.4			
3	0.664	1.73	2.05	34.5	208.8	14.7			
4	0.664	1.77	1.97	31.5	189.8	13.3			
g-1	0.662	2.36	2.24	40.5	120.7	8.46			
2	0.662	2.08	1.97	37.5	163.3	11.5			
3	0.662	1.85	1.93	31.5	178.0	12.5			
4	0.662	1.85	1.97	24.0	134.4	9.45			
5	0.662	1.69	1.73	22.5	170.4	12.0			

Table B5. Processed snow-compacted runway.

a-1	0.570	5.063	3.688	32.25			3.0	8.64	0.61
2	0.570	5.8	3.1	104.25			3.0	28.40	2.00
3	0.578	5.6	3.0	57.75	23.7	1.67			
4	0.590	4.0	3.0	21.75			5.0	11.4	0.80
5	0.590	5.5	3.1	50.25			4.5	13.5	0.95
6	0.620	5.6	3.3	18.75	8.27	0.58			
7	0.620	6.0	3.5	20.25	7.43	0.52			
8	0.628	6.0	2.9	39.75			1.5	13.63	0.96
9	0.639	6.0	3.0	107.25			2.0	31.40	2.20
10	0.659	3.2	3.2	71.25			4.0	55.1	3.87
11	0.650	4.3	2.7	105.75	76.6	5.53			
12	0.639	5.0	3.2	98.25			4.5	29.3	2.06
b-2	0.578	5.2	3.2	39.75			3.5	13.30	0.93
3	0.589	5.1	2.8	38.25	20.75	1.45			
4	0.601	5.2	3.0	87.75			2.0	34.18	2.40
5	0.614	5.6	3.2	96.75			2.0	30.61	2.15
6	0.620	4.0	3.4	92.25	63.44	4.46			
7	0.620	4.0	2.75	122.25	7.20				
8	0.626	3.4	2.9	71.25	79.54	5.59			
9	0.628	4.0	2.6	54.75				37.81	2.66
10a	0.628	2.6	3.3	30.75	53.33	3.74			
10b	0.628	2.9	3.4	17.25			1.5	22.32	1.57
11	0.628	4.0	2.5	56.25			1.0	48.86	3.43
12	0.620	4.1	3.4	122.25	79.63	5.60			
13	0.609	3.4	2.9	59.25	66.55	4.68			
c-1	0.512	5.7	2.7	77.25	33.1	2.33			
3	0.545	5.6	2.8	63.75			2.5	22.1	1.55
4	0.576	5.5	3.2	105.75	40.9	2.88			
5	0.620	3.7	3.2	41.25	36.7	2.58			
6	0.609	3.2	3.3	57.75	64.2	4.51			
7	0.601	2.8	3.5	71.25	96.9	6.80			

Table B5 (Cont'd) Processed snow-compacted runway.

Beam	Density ρ (g/cm³)	Height h (in.)	Width b (in.)	Load P (lb)	Max stress at center, σ (psi)	(kg/cm³)	Break off center (in.)	Strength at break (psi)	(kg/cm²)
c-8	0.601	2.8	3.1	32.25	51.0	3.58			
9	0.601	2.9	2.5	23.25	43.0	3.02			
10	0.590	3.2	3.4	30.75			2.0	29.3	2.06
11	0.578	3.2	2.5	35.25			3.0	39.9	2.80
12	0.578	3.8	3.3	59.25			1.0	43.6	3.06
13	0.584	3.8	2.8	71.25			1.5	58.2	4.09
d-1	0.540	3.9	3.3	48.75	37.2	2.61			
2	0.529	3.8	3.6	57.75			3.0	32.0	2.25
3	0.520	4.0	3.0	23.25	19.4	1.36			
4	0.495	4.2	3.0	21.75	16.6	1.27			
5	0.551	4.0	3.2	26.25			2.0	17.5	1.23
6	0.570	3.6	3.4	39.75			1.0	32.3	2.27
7	0.570	3.8	3.4	32.25			1.0	24.0	1.69
8	0.570	3.8	3.1	26.25	23.4	1.64			
9	0.570	3.6	2.5	33.75	39.9	2.80			
10	0.559	3.6	2.5	42.75	49.9	3.51			
11	0.559	3.4	2.3	11.25	17.8	1.25			
12	0.570	3.3	3.2	14.25			1.0	16.1	1.13
13	0.590	3.4	2.9	15.75	19.6	1.38			
e-4	0.551	4.0	3.1	14.25	12.5	0.88			
5	0.473	5.5	3.4	51.75	19.5	1.37			
6	0.520	6.2	3.4	62.25			2.0	15.5	1.09
7	0.565	5.3	3.1	102.75			1.0	40.7	2.86
8	0.601	4.1	3.2	63.75	45.0	3.16			
9	0.559	4.2	3.4	29.75	19.6	1.38			
10	0.551	4.2	2.1	32.25			3.0	25.6	1.80
12	0.526	4.2	3.1	32.25			1.5	20.6	1.45
13	0.645	4.4	3.1	45.75	29.8	2.09			

Table B6. Processed snow-Peter miller.

Production trench pile

a-1	0.520	4.25	2.40	24.0			1.0	20.2	1.42
2	0.558	3.98	3.07	25.5			1.0	19.5	1.38
3	0.59	4.41	2.99	61.5			2.0	33.8	2.38
4	0.564	4.49	2.44	49.5	31.6	2.23			
5	0.558	4.25	3.27	34.5	23.1	1.62			
b-1	0.561	4.29	2.28	12.0			1.0	11.5	0.81
2	0.582	4.17	2.87	45.0			1.0	32.1	2.26
3	0.604	4.06	2.76	36.0			1.0	28.5	2.00
4	0.592	3.78	2.87	39.0	36.9	2.60			
5	0.578	4.29	3.15	15.0	11.4	0.80			
c-2	0.55	3.74	3.07	21.0			3.0	15.4	1.08
3	0.539	3.82	2.91	12.0			2.0	10.6	0.75
4	0.546	3.98	2.83	12.0	11.7	0.83			
5	0.575	3.39	3.23	13.5	16.7	1.18			
d-1	0.583	3.78	2.76	24.0	24.4	1.72			
2	0.590	4.49	3.07	37.5	23.9	1.68			

Arch backfill

1	0.510	3.94	1.42	13.5	24.1	1.70			
2	0.510	3.19	1.84	9.0	19.8	1.39			
3	0.545	3.66	2.00	19.5	28.6	2.02			
4	0.580	3.23	2.39	6.0	12.2	0.86			
5	0.615	3.42	2.75	9.0	12.9	0.91			
6	0.56	4.96	1.42	30.0	32.8	2.31			
7	0.538	4.65	1.96	13.5			0.5	12.7	0.90