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1 Report

Soil Freezing

2 Reports

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Contents

Permeable Materials for Highway Drainage

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Although most highway departments design for saturated roadbed conditions, the removal of excess water to prevent prolonged flooding is necessary if maximum performance is to be obtained. Recognizing the need for adequate internal drainage of highways the California Division of Highways has been experimenting with various gradings in an effort to utilize blends of readily available concrete aggregates in drainage systems. The paper reviews past specifications for "permeable materials" and gives the results of an extensive series of laboratory permeability tests which were used in developing grading limits for a new class of permeable material. Gradation curves and permeabilities are given for typical combinations tested. Basic data for all of the tests are summarized in tables. The paper includes a brief discussion of a method for estimating the water-removing capabilities of blankets of permeable aggregates and a chart evaluating typical layers. Alternative designs utilizing two-layer systems are noted as a means for draining highway pavements when large quantities of water are anticipated.

•THE California Division of Highways tries to construct highway roadbeds so that they will not be prematurely damaged by traffic. Design soil strengths are determined by testing subgrade and base materials in a saturated condition (1). The intent is to obtain roads that will not be damaged by water entering the structural section, either through the surface, the shoulders, or from groundwater sources. Inasmuch as the climate in California varies from the extremely hot and dry Death Valley to the wet and cool north coastal areas and soil conditions are equally variable, it is frequently necessary to modify the California Standard Specifications by issuing special provisions for individual contracts for construction projects. Each job is designed to function for the conditions as they exist on that project. Throughout much of the state, water causes problems of instability; hence, "permeable materials" have been widely used in underdrains, pervious blankets, and stabilization trenches. The problem of using the right kind of aggregates to remove water quickly without clogging is a very difficult one. The problem has been studied for years, and the state has varied its practices in an attempt to do the best drainage job at least cost. From time to time, new classes of aggregates have been specified for drainage purposes. This paper describes a series of tests that were made using undersanded concrete aggregate mixtures in the development of a new class of permeable material now called Class 3.

BACKGROUND

Some of the trends in selecting aggregates for drainage purposes are given in Table 1. Before 1945, coarse material grading from 1 in. to 6 in. in size was used

Paper sponsored by Committee on Subsurface Drainage.

TABLE 1

SOME DRAINAGE AGGREGATES USED IN CALIFORNIA

Year of Stand. Specs.	Grading Requirements - % Passing													
	6 In.	$2\frac{1}{2}$ In.	2 In.	$1\frac{1}{2}$ In.	1 In.	$\frac{3}{4}$ In.	$\frac{3}{8}$ In.	No. 4	No. 8	No. 16	No. 30	No. 50	No. 100	No. 200
1927	100				0									
1940	100					0								
1945		100				40-100		15-50	5-30		0-5			0-2
1949		100				40-100		15-50	5-30		0-5			0-2
1954 Type A						100		80-100	60-90		20-50	10-25		0-4
Type B				100		90-100		55-85	35-65		15-35	10-25		0-3
Type C		100		80-100		60-95		35-65	25-50		5-25			0-3
1960 Type A							100	90-100						
Type B				100		90-100	65-85	45-65						
Type C			100	90-100		60-80		40-60						
- No. 4								100	65-90	45-70	20-40	8-16	0-4	0-2

for drain rock. In 1945 a graded aggregate from $2\frac{1}{2}$-in. maximum size down to the No. 200 sieve was specified. This grading was retained in the 1949 Standards, but in 1954 three classes (A, B, and C) were established. Class A was a fine-graded material $\frac{3}{4}$ in. and finer in size, Class B graded from $1\frac{1}{2}$-in. maximum and Class C from $2\frac{1}{2}$-in. maximum. Since 1954 further changes have been made with more classes established to give greater choice of sources for permeable material. The trend in recent years has been toward graded aggregates with sufficient fines to prevent the intrusion of soil into drainage systems. This practice came about because of bad experiences with the open rocks used before 1945. Many of the old drains were dug into a number of years after construction, and of those which had failed to function, a large percentage were found to have become badly clogged with soil. Some of these drains, chiefly those which had been installed in firm, resistant, or rocky formations, were still unclogged.

With the change to graded aggregates for drainage purposes control over the amount of fines in the aggregates became extremely important. Small increases in the amount of fines in graded aggregates can alter the permeability very markedly (Table 2). If the grading of these materials is not properly controlled their permeabilities can be so low that their capabilities for removal of water are greatly impaired. During the time that the 1960 Specifications were in force a considerable number of proposed or used aggregates were tested for permeability. Some typical results are given in Table 3.

In the study of drainage aggregates for removing water, it is useful to know how much water various aggregates can remove. If the permeability and hydraulic gradient are known or can reasonably be approximated, one can readily compute water-removing capacity. To develop Figure 1, the quantities of water that can be removed by relatively flat blankets of aggregate were calculated from Darcy's law,

$$Q = k\ i\ A \tag{1}$$

where Q represents the quantity of water that can flow in an aggregate layer with a coefficient of permeability; k is a hydraulic graident; i is assumed equal to the slope of the pavement; and A is a cross-sectional area. The lines (Fig. 1) are for flow through a 1-sq ft area. Hence, the quantities are those that can be removed by 1 sq ft of cross-sectional area. It can be 1 ft deep by 1 ft wide, 6 in. deep by 2 ft wide, etc. For example, Figure 1 shows that a material with a permeability of 10 ft/day on a 2 percent slope is capable of removing about 0.2 cu ft/day or 1.5 gal/day for each square foot of area. A material with a permeability of 100 ft/day can remove 2 cu ft or 15 gal per day.

Figure 1 points up the general nature of seepage within relatively flat drainage layers, such as those often constructed beneath highways. The water-removing potential of unit area varies with the per-

TABLE 2

PERCENT OF FINES VS PERMEABILITY[a]

% Passing No. 100	Test k (ft/day)
0	80-300
1	35-200
2	10-100
4	2-50
6	0.5-20
7	0.2-15

[a]Graded filter aggregate.

TABLE 3

TYPICAL DATA FOR 1960 PERMEABLE MATERIALS[a]

Test No.	Grading Analysis (% Passing)									Impact Test Max. Dens. (pcf)	Permeability at 95% R. C. (ft/day)
	¾ In.	⅜ In.	No. 4	No. 8	No. 16	No. 30	No. 50	No. 100	No. 200		
56-613	100	90	54	39	26	15	9	8	4	127	3
57-1146		100	98	90	65	41	18	5	3	123	5
57-1197-A	95	72	60	52	40	25	11	4	2	134	4
60-1743-A	100	79	64	56	44	23	16	5	2	133	2
60-1745-A	100	71	51	40	31	23	12	4	2	138	3
60-2369	100	72	53	41	27	14	6	3	1	130	14
60-2840	100	82	74	66	52	33	15	6	3	127	12
60-3919	100	92	91	78	60	38	16	8	3	124	7
60-3918	100	58	42	35	29	19	10	4	4	134	2
60-4010-B	100	64	40	28	15	7	4	3	1	129	30
61-581-A	100	75	51	41	29	19	8	2	2	137	4
61-583-A	100	77	54	46	36	20	13	4	2	136	3
61-799	100	77	58	46	35	18	7	4	3	134	14
61-1575	100	97	54	37	24	15	6	2	2	135	10
61-1856	91	65	50	40	30	19	10	4	3	135	8
61-2421	100	79	60	46	31	19	9	4	3	132	6
61-2422	100	84	72	62	50	36	19	7	5	132	1

[a]Samples did not all pass 1960 Specifications; many were preliminary and were not used in the construction of highways.

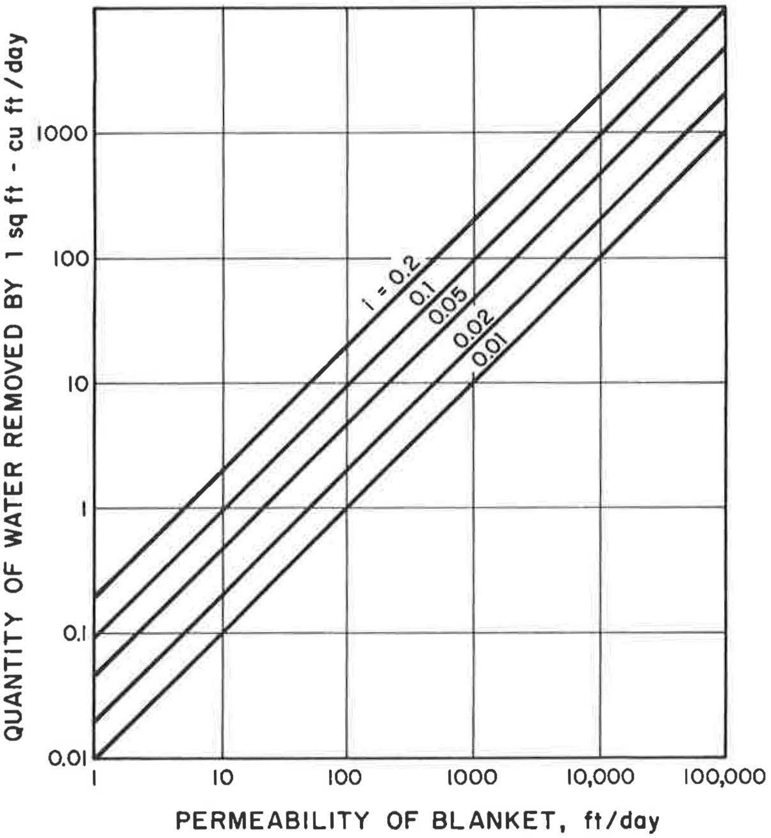

Figure 1. Water-removing capabilities of drainage blankets.

meability and the hydraulic gradient. If large quantities of water are anticipated, it is often necessary to specify high permeability aggregates, with little or no material finer than the No. 8 sieve. When these open-graded aggregates are used no erodible material can be in contact with the layer or the layer may become plugged by intrusion in the same way that French drains often become clogged. When this danger exists the open-graded aggregates must be separated from the erodible material by an intermediate layer of graded aggregate through which the material cannot move. Various "filter" criteria are available for establishing gradings that will provide permanent protection (2, 3, 4, 5). A system composed of two or more filter layers is called a "graded filter" (6). They have been a standard feature in the design of dams and levees for several decades, but have been rarely used in highway drainage. In situations where large quantities of water must be removed and erodible soils occur, they can often provide an economical solution. In other locations where moderate quantities of water are anticipated, the graded aggregates studied in the program are often used.

Materials meeting the 1960 specifications could be produced by blending fine and coarse concrete aggregate. In order to do this the concrete aggregates had to be toward the clean side of the specifications, the aggregate had to be relatively hard and durable, and care was necessary in blending, handling, and placing. The minus No. 4

TABLE 4

SUMMARY OF TEST DATA — PRELIMINARY TESTS

Sample No.	Grading Analysis - % Passing											Sand (%)	Impact Test Max. Density (pcf)	Permeability at 95% R. C. (ft/day)
	1 In.	3/4 In.	1/2 In.	3/8 In.	No. 4	No. 8	No. 16	No. 30	No. 50	No. 100	No. 200			
62-3480 F. sc.				100	48	6	1	1	1	1	1	0	114	4,000-5,000
Combined				100	63	26	16	10	5	2	2	25	123	140-160
samples				100	76	44	31	19	9	4	2	50	130	25-35
Conc. sand-lab stockpile					100	82	59	35	11	4	2	100	122	9-10
62-3479 M. sc.			100	98	9	2	2	2	1	1	1	0	114	7,000-8,000
Combined			100	99	27	18	13	9	4	3	2	20	124	140-150
samples			100	99	45	34	24	15	7	3	2	40	133	17
Conc. sand-lab stockpile					100	82	59	35	11	4	2	100	122	9-10
62-3478 C. sc.			100	47	5	2	1	1	1	1	1	0	116	11,000
Combined			100	55	20	14	10	6	3	2	2	15	123	1,500-2,000
samples			100	65	34	26	19	12	6	3	2	30	130	40-50
			100	76	53	42	31	19	10	3	2	50	132	28-30
Conc. sand-Lab stockpile					100	82	59	35	11	4	2	100	122	9-10
62-3926 P. gr.			100	95	33	8	2	0				0	119	2,500
Combined			100	96	44	24	14	8	3	2	2	20	128	70-80
samples			100	97	60	40	25	14	7	3	3	40	131	35-40
62-3927 Conc. sd.					100	88	59	29	15	5	5	100	120	30-35
62-4040 1 in. × No. 4 conc. ag.	96	70	33	15	0							0	121	3,200-4,000
Combined	97	77	46	32	19	14	10	7	4	1	1	20	131	30-40
samples	98	84	59	49	37	28	21	14	7	2	2	40	135	11-12
62-4039 Conc. sd.				100	92	71	51	35	20	7	5	100	122	8-10
62-4037 F. sc.				100	47	9	3	2	1	0		0	113	4,000-6,000
Combined				100	58	21	12	9	5	1	1	20	120	90-100
samples				100	65	33	23	15	8	3	2	40	128	24-30
62-4039 Conc. sd.				100	92	71	51	35	20	7	5	100	122	8-10
62-4038 Med. scr.				100	48	0						0	112	18,000-22,000
Combined				100	57	14	10	6	4	1	1	20	122	54-74
samples				100	69	28	21	14	8	3	2	40	128	22-24
62-4039 Conc. sd.				100	92	71	51	35	20	7	5	100	122	8-10
62-4036 C. sc.		100	92	70	3	1	0					0	116	10,000-11,000
Combined		100	94	76	21	14	10	7	4	1	1	20	129	50-60
samples		100	96	83	39	29	21	14	8	3	2	40	134	27-30
62-4039 Conc. sd.				100	92	71	51	35	20	7	5	100	122	8-10
62-4034 F. scr.				100	55	1	0					0	112	1,800-2,700
Combined				100	60	16	10	6	3	1	1	20	118	110-130
samples				100	70	33	20	9	5	2	1	40	123	60-68
62-4035 Conc. sd.				100	96	79	49	32	13	4	2	100	125	25
62-4031 3/4 in. × No. 4 conc. agg.		100	57	33	7	1	0					0	120	13,000-15,000
Combined		100	66	47	29	16	10	6	3	1	1	20	131	90-120
samples		100	74	61	42	32	20	13	5	2	1	40	137	20-25
62-4035 conc. sd.				100	96	79	49	32	13	4	3	100	125	25
62-4033 Med. scr.			100	97	23	14	8	5	2	1	1	0	113	3,000
Combined			100	98	37	27	16	10	5	2	2	20	124	90
samples			100	99	53	40	25	16	6	3	2	40	128	42
62-4035 conc. sd.				100	96	79	49	32	13	4	3	100	125	25
62-4032 c. scr.		100	97	64	8	2	1	1	1	1	1	0	113	12,000-13,000
Combined		100	97	73	25	17	11	7	4	2	2	20	123	120-150
samples		100	98	77	44	33	21	14	6	3	2	40	132	30-40
62-4035 conc. sd.				100	96	79	49	32	13	4	3	100	125	25

fraction could not contain more than 2 percent minus No. 200 material. Hence, the maximum allowable minus No. 200 in the permeable material was usually 1 percent or less. Producers found this difficult to achieve particularly if pit run material was soft or the percentage of fines was high.

The possibilities of using an undersanded mixture of coarse and fine concrete aggregate for permeable material to achieve somewhat higher permeability were known. One disadvantage of this material is the possibility of segregation and the resultant low permeability in the fine portion or infiltration in the coarse portion.

F. N. Hveem, Materials and Research Engineer (retired October 1963), felt that any disadvantages resulting from segregation might be more than compensated for by ease of production and higher permeability and directed the laboratory study. The tests were performed on readily available commercial aggregates.

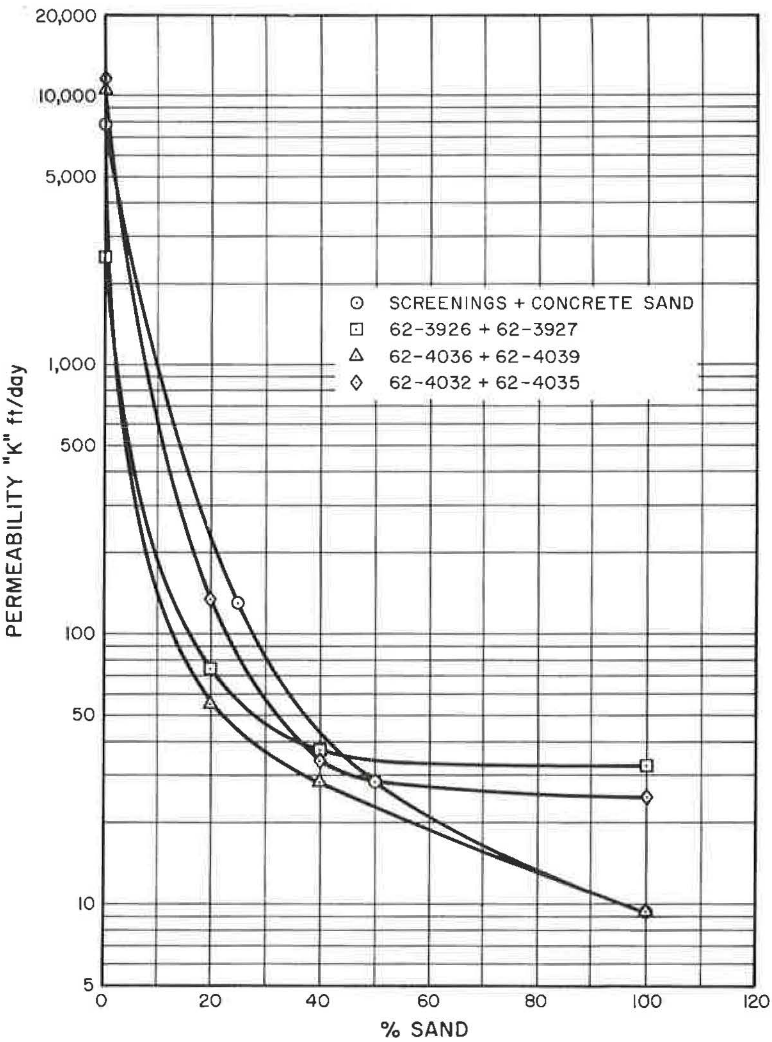

Figure 2. Permeability k vs percent sand.

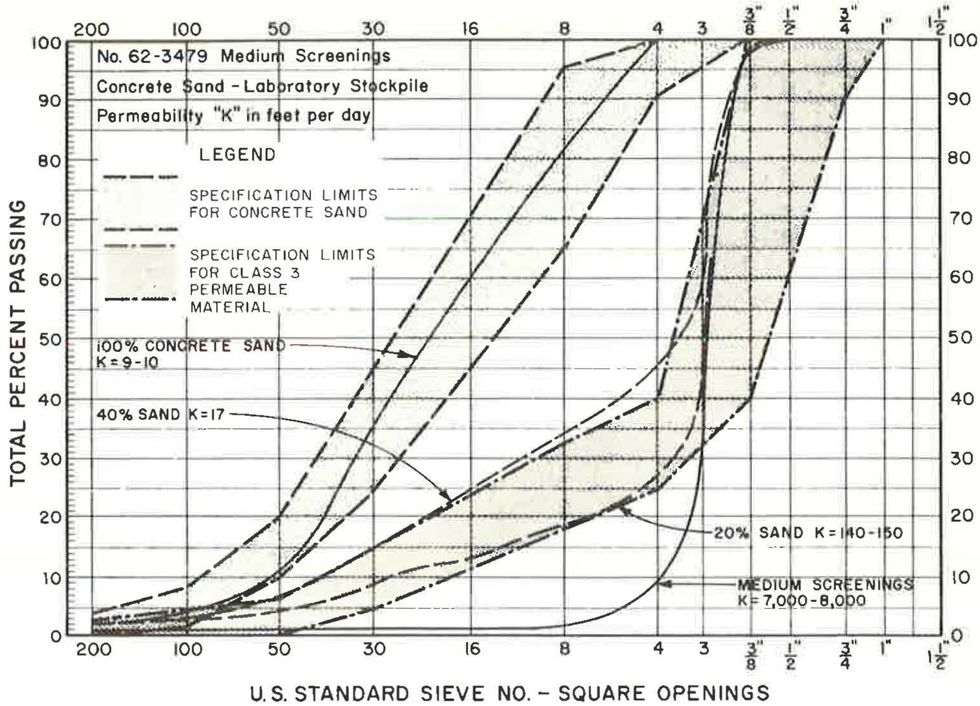

Figure 3. Grading curves for fine screenings and concrete sand (preliminary tests).

TESTING PROGRAM

Preliminary Tests

During the summer of 1962 samples of concrete sand and ¾ in. by No. 8 coarse aggregate were obtained from four aggregate producers. Constant-head permeability tests were run on each of the sand and aggregate samples and various combinations of the sand and the aggregate. These tests were made in 6-in. diameter constant-head permeameters using California Test Method No. 220-B. Specimens are tested using various compactive efforts and plots of permeability versus density are prepared. The results of this series are given in Table 4 and typical data are shown in Figures 3 through 7. The permeabilities of the combinations range from the same as the sand alone to about 4 times the permeability of the sand when the combinations contain approximately 60 percent of the aggregate. When the percent of aggregate in the combination was increased to 75 percent, the permeability ranged from 4 to 15 times that of the sand alone (Fig. 2). However, when the percentage of sand in the combination was 25 percent or lower, segregation of the coarse and fine portions was evident when the material was being placed in the test mold. This is in agreement with experience on construction projects with undersanded aggregates. It was therefore recognized that care would have to be exercised in placing such aggregates in highway construction to minimize segregation.

The findings of this testing, coupled with previous experience with various gradings or permeable materials, led to the development of the following grading specification for Class 3 permeable material:

Sieve Size	Percent Passing	Sieve Size	Percent Passing
1 In.	100	No. 8	18-33
¾ In.	90-100	No. 30	5-15
⅜ In.	40-100	No. 50	0-7
No. 4	25-40	No. 200	0-3

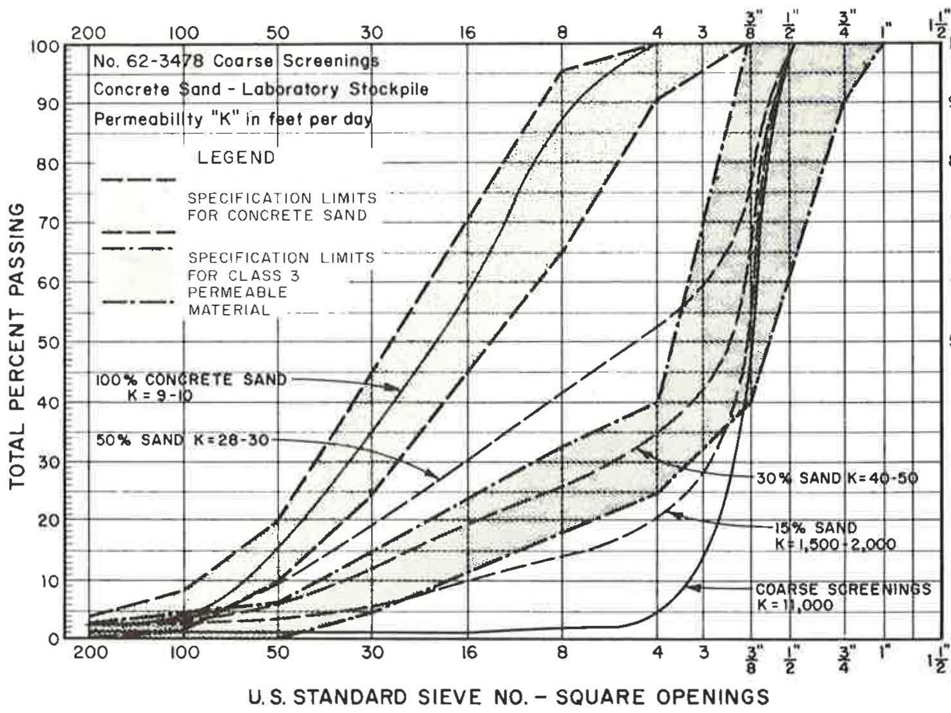

Figure 4. Grading curves for fine screenings and concrete sand (preliminary tests).

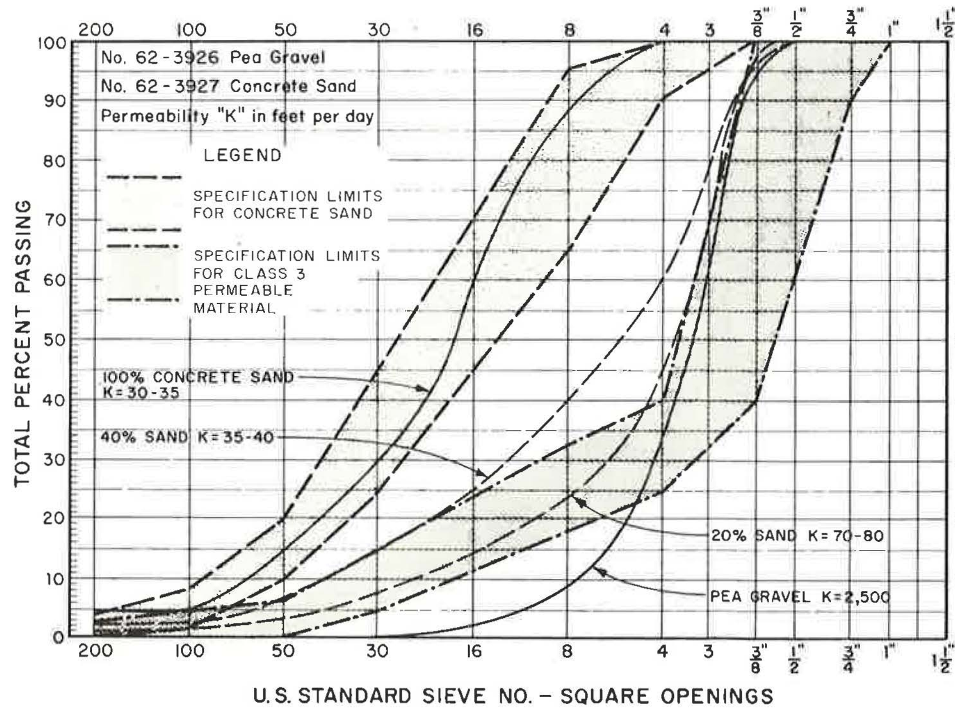

Figure 5. Grading curves for fine screenings and concrete sand (preliminary tests).

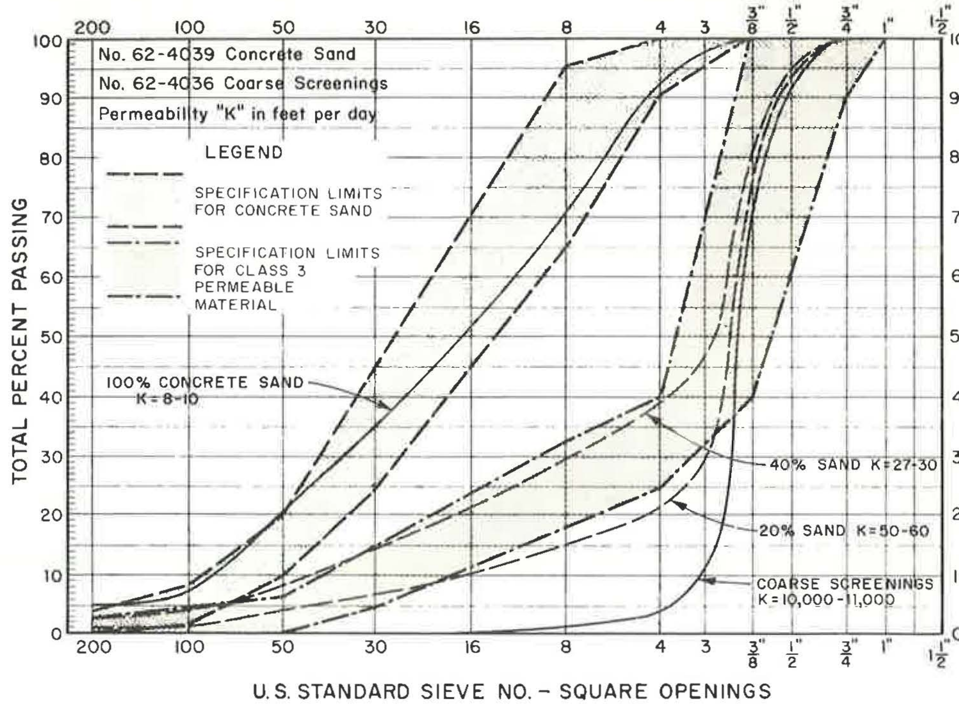

Figure 6. Grading curves for fine screenings and concrete sand (preliminary tests).

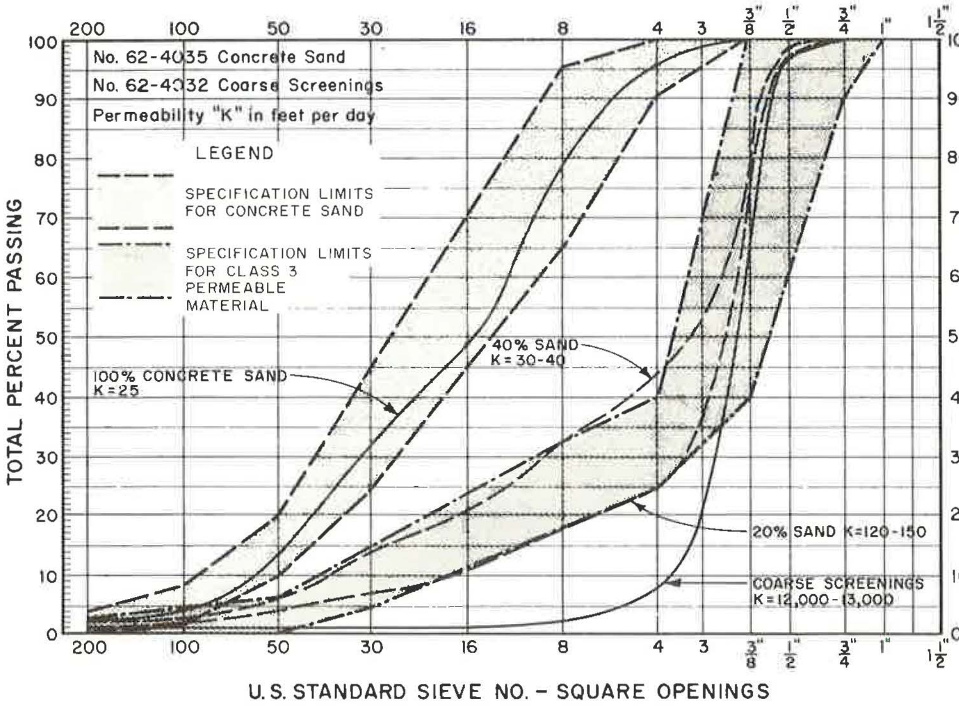

Figure 7. Grading curves for fine screenings and concrete sand (preliminary tests).

Additional Tests

In September 1962, a letter was sent to eight California Highway Districts asking for fine concrete aggregate, ¾ in. by No. 4 concrete aggregate, and permeable material sampled from plants which supply significant amounts of these aggregates for highway projects. The districts asked to participate in this sampling represented those using substantial amounts of permeable materials. A total of 70 samples were received; three were representative of the 1960 Standard Specification filter material, 32 were representative of fine concrete aggregate, and the remaining 35 were of various sizes of coarse concrete aggregate. Of the 32 fine concrete aggregate samples, 11 did not meet the California grading specifications for fine concrete aggregate, and one had a sand equivalent less than 70. These materials were used, since it was desired to obtain information about blends of borderline materials--those high in fines.

The coarse aggregate samples were scalped on the ¾-in. sieve, where necessary, and combined with the sand fraction so that the combined grading would be on the fine side of the Class 3 specifications. Three sources could not be combined to meet the Class 3 grading specifications without altering the as-received grading.

Sand equivalent tests were performed on the fine concrete aggregate samples, and a California durability test was performed on all samples. The maximum density was determined, by the California impact test, on all combinations of gradings used in the permeability tests. Permeabilities are given for specimens compacted to 95 percent of the maximum density determined by the impact test.

The test data are given in Table 5. Typical gradings of the combined samples are plotted (Figs. 8 through 14) and the value of k, the coefficient of permeability, is shown beside each grading curve.

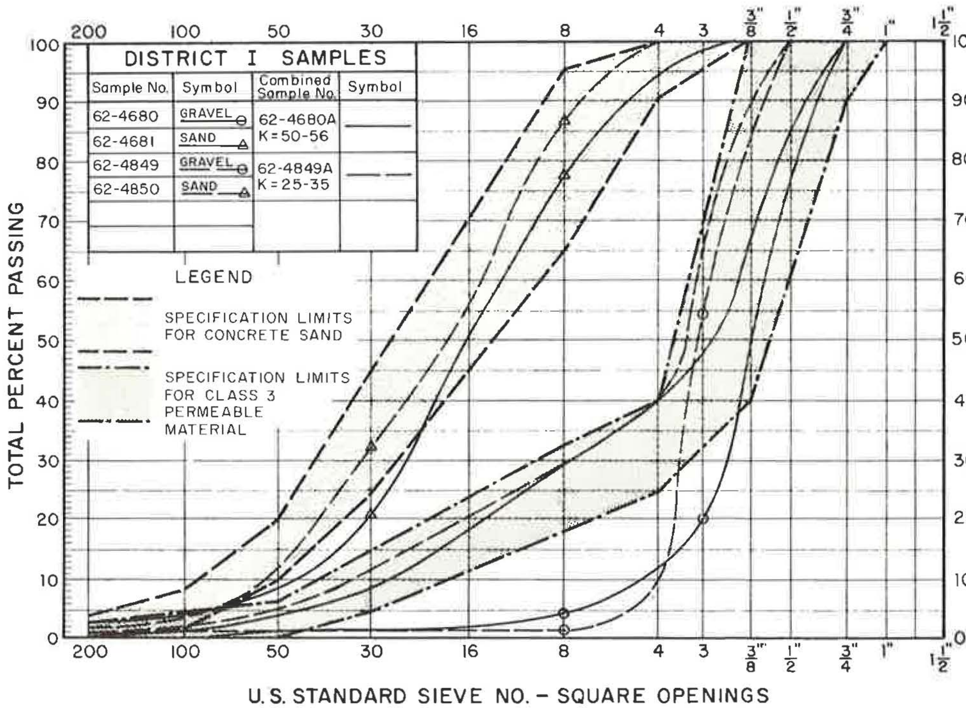

Figure 8. Grading curves for sand and gravel (additional tests).

TABLE 5

SUMMARY OF TEST DATA—ADDITIONAL TESTS

Sample No.	Grading Analysis % Passing											Sand (%)	S. E.	Impact Test Max. Density (pcf)	Permeability k at 95% R. C. (ft/day)	Durability Factor (D)
	1 In.	3/4 In.	1/2 In.	3/8 In.	No. 4	No. 8	No. 16	No. 30	No. 50	No. 100	No. 200					
DIST. I:																
62-4680 As recd.	100	98	75	49	12	4	2	1	1	0	0					76
62-4680 As used		100	77	50	12	4	2	1	1	0	0					
62-4681				100	94	77	50	21	8	4	3		92			70
62-4680A		100	85	67	40	29	18	8	4	1	1	34		134	50-56	
62-4849			100	84	10	1	1	1	1	1	0					60
62-4850					100	86	57	32	12	3	2		89			46
62-4849A			100	89	40	29	20	12	5	2	1	33		131	25-35	
DIST. II:																
62-4584 As recd.	100	97	51	18	2	1	1	1	1	1	1					78
62-4584 As used		100	53	19	2	1	1	1	1	1	1					
62-4585				100	90	82	66	40	16	4	2		91			74
62-4584A		100	70	48	36	31	25	15	6	2	2	36		139	19-24	
62-4586 As recd.	100	96	72	30	1	0	0	0	0	0	0					59
62-4586 As used		100	75	31	1	0	0	0	0	0	0					
62-4587				100	99	90	76	51	19	5	2		90			75
62-4586A		100	83	52	31	27	23	15	6	2	0	30		134	20-30	
62-4588 As recd.	100	92	45	22	0	0	0	0	0	0	0					74
62-4588 As used		100	49	24	0	0	0	0	0	0	0					
62-4589				100	94	78	52	34	19	8	4		77			63
62-4588A		100	69	54	37	30	20	13	7	3	2	39		138	9-10	
62-4588B		100	64	47	28	23	16	10	6	2	1	30		134	45-60	
DIST. III:																
62-4581 As recd.	100	99	75	42	2	1	1	0	0	0	0					85
62-4581 As used		100	76	42	2	1	1	0	0	0	0					
62-4582				100	93	77	67	47	21	6	3		82			63
62-4581A		100	84	61	31	26	22	15	7	2	1	32		139	15-25	
62-4638 As recd.	100	96	40	12	2	1	1	1	1	0	0					78
62-4638 As used				100	0	0	0	0	0	0	0					
62-4639				100	92	78	54	36	18	7	5		88			73
62-4638A				100	46	39	27	18	9	4	3	50		134	10-12	
62-4638B				100	40	34	23	15	8	3	2	43		134	10-13	
62-4642 As recd.	100	91	55	33	4	1	1	1	0	0	0					73
62-4642 As used		100	60	36	4	1	1	1	0	0	0					
62-4643					100	79	54	35	17	5	3		76			68
62-4642A		100	75	60	40	31	22	14	6	2	1	38		136	17-23	
62-4827 As recd.	100	75	29	14	1	1	1	1	0	0	0					82
62-4827 As used		100	39	19	1	1	1	1	0	0	0					
62-4828				100	95	82	66	43	14	6	3		92			82
62-4827A		100	59	46	32	28	23	15	5	2	1	33		133	21-26	
62-4829 As recd.	99	86	50	28	1	0	0	0	0	0	0					93
62-4829 As used		100	58	33	1	0	0	0	0	0	0					
62-4830				100	87	57	43	29	14	4	2		98			82
62-4829A		100	75	60	36	23	17	12	6	2	1	40		131	25-30	
62-5004		100	55	23	3	2	1	1	1	1	1					76
62-5005				100	93	78	60	41	20	6	3		94			72
62-5004A		100	69	48	32	26	20	14	7	3	2	32		127	27-33	
DIST. IV:																
62-4607 As recd.	100	89	55	29	1	0	0	0	0	0	0					70
62-4607 As used		100	62	33	1	0	0	0	0	0	0					
62-4608				100	97	81	62	41	16	5	3		88			73
62-4607A		100	76	58	37	30	23	15	6	2	1	37		134	28-35	
62-4609 As recd.	100	92	25	6	1	1	1	1	1	1	0					54
62-4609 As used		100	27	7	1	1	1	1	1	1	0					
62-4610				100	97	77	53	35	18	8	6		81			37
62-4609A		100	67	50	40	32	22	14	7	4	2	41		138	9-12	
62-4609B		100	65	55	50	40	28	18	9	4	3	48		137	9-12	
62-4611 As recd.	100	99	76	41	6	2	1	1	1	1	1					78
62-4611 As used		100	77	41	6	2	1	1	1	1	1					
62-4612					100	91	55	30	14	6	4		82			62

62-4616				100	91	63	45	28	12	4	3		86			63
62-4615A		100	81	63	37	26	19	11	5	2	1	40		134	23-35	
62-4617 As recd.	100	86	23	3	1	1	1	1	1	1	0					46
62-4617 As used		100	27	3	1	1	1	1	1	1	0					
62-4618				100	99	91	54	34	16	4	2		85			46
62-4617A		100	48	37	36	33	20	13	7	2	1	35		134	28-35	
62-4619 As recd.	100	95	52	16	1	0	0	0	0	0	0					67
62-4619 As used		100	55	17	1	0	0	0	0	0	0					
62-4620				100	99	58	33	15	5	2			88			67
62-4619A		100	70	45	34	33	19	11	5	2	1	33		134	20-30	
DIST. V:																
62-4929 As recd.	98	71	37	19	1	1	1	1	1	0	0					78
62-4929 As used		100	52	27	1	1	1	1	1	0	0					
62-4930				100	86	65	45	23	8	3	1		94			85
62-4929A		100	70	54	33	29	24	15	5	1	0	33		131	20-30	
62-4931 As recd.	100	99	64	35	3	2	1	1	1	1	0					76
62-4931 As used		100	65	35	3	2	1	1	1	1	0					
62-4932						100	77	43	21	6	4		84			66
62-4931A		100	76	55	32	31	25	14	7	3	1	30		130	23-33	
62-4933 As recd.	97	77	43	24	1	0	0	0	0	0	0					78
62-4933 As used		100	56	31	1	0	0	0	0	0	0					
62-4928				100	98	89	74	46	16	3	1		91			85
62-4933A		100	70	54	33	29	24	15	5	1	0	33		131	20-30	
62-4934 As recd.	100	96	49	21	2	1	1	1	1	1	1					80
62-4934 As used		100	51	22	2	1	1	1	1	1	1					
62-4935					100	89	60	36	18	9	6		77			66
62-4934A		100	◆ 86	54	32	28	19	12	7	4	3	30		144	13-17	
DIST. VII:																
62-4694 As recd.	100	67	9	2	1	1	1	1	1	1	1					62
62-4694 As used		100	13	3	1	1	1	1	1	1	1					
62-4695					100	83	53	25	11	7	6		65			71
62-4694A		100	58	52	41	34	22	11	5	4	3	40		133	15-19	
62-4696 As recd.	98	87	60	35	6	3	2	2	1	1	1					82
62-4696 As used		100	69	40	7	3	2	2	1	1	1					
62-4697				100	96	83	69	47	20	5	2		93			86
62-4696A		100	78	58	34	32	22	15	7	2	1	30		134	10-13	
62-4763 As recd.	98	81	43	19	2	1	1	1	1	1	1					73
62-4763 As used		100	53	23	2	1	1	1	1	1	1					
62-4764				100	96	84	70	44	18	5	2		89			81
62-4763A		100	68	48	32	28	23	15	7	3	2	32		132	15-19	
62-4777 As recd.	100	86	14	4	1	1	1	1	1	0	0					82
62-4777 As used		100	16	5	1	1	1	1	1	0	0					
62-4778				100	98	85	65	41	20	7	4		82			78
62-4777A		100	44	38	35	30	24	15	8	3	1	35		137	6-8	
DIST. X:																
62-4626 As recd.	100	95	53	29	4	2	1	1	1	1	1					82
62-4626 As used		100	56	31	4	2	1	1	1	1	1					
62-4627				100	97	85	68	41	16	5	3		89			83
62-4626A		100	71	55	37	31	25	15	7	3	2	35		135	13-18	
62-4628 As recd.	100	98	74	39	3	1	0	0	0	0	0					70
62-4628 As used		100	76	40	3	1	0	0	0	0	0					
62-4629				100	99	83	66	45	15	3	2		85			78
62-4628A		100	84	60	36	29	22	15	5	1	1	34		135	27-34	
62-4735			100	95	9	0	0	0	0	0	0					76
62-4736				100	98	88	71	38	14	5	2		90			78
62-4735A			100	97	40	31	25	12	5	2	1	35		132	24-34	
DIST. XI:																
62-4842 As recd.	100	87	44	23	3	2	1	1	1	1	0					59
62-4842 As used		100	51	26	3	2	1	1	1	1	0					
62-4843				100	92	73	60	43	17	5	2		81			52
62-4842A		100	67	50	32	25	21	15	7	3	1	33		127	32-42	
62-4844 As recd.	100	96	46	12	0	0	0	0	0	0	0					78
62-4844 As used		100	48	13	0	0	0	0	0	0	0					
62-4845					100	88	69	41	20	8	4		83			81
62-4844A		100	56	35	26	23	18	11	7	2	1	26		126	45-60	
62-4846		100	45	16	2	1	1	1	1	0	0					71
62-4847				100	95	76	58	42	13	3	1		89			61
62-4846A		100	64	45	33	27	21	15	5	1	0	34		126	45-60	

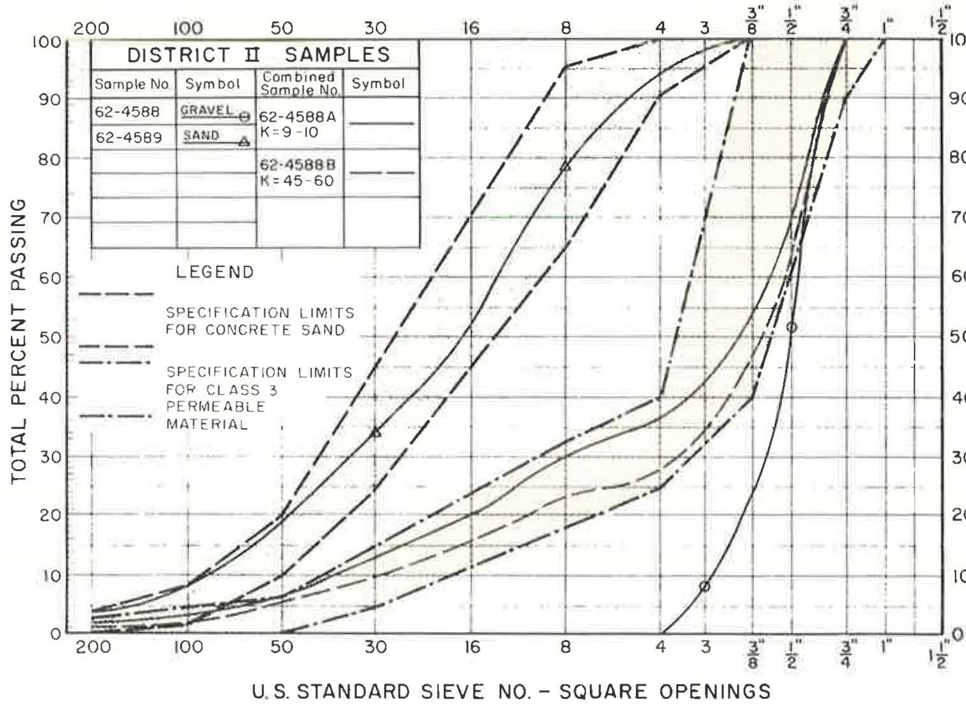

Figure 9. Grading curves for sand and gravel (additional tests).

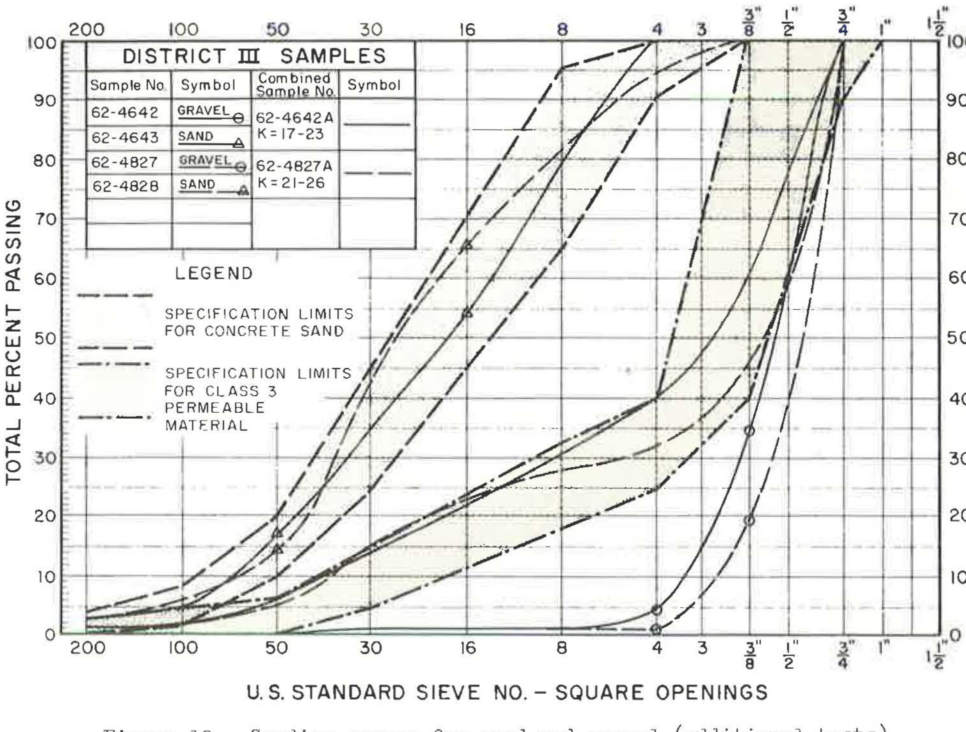

Figure 10. Grading curves for sand and gravel (additional tests).

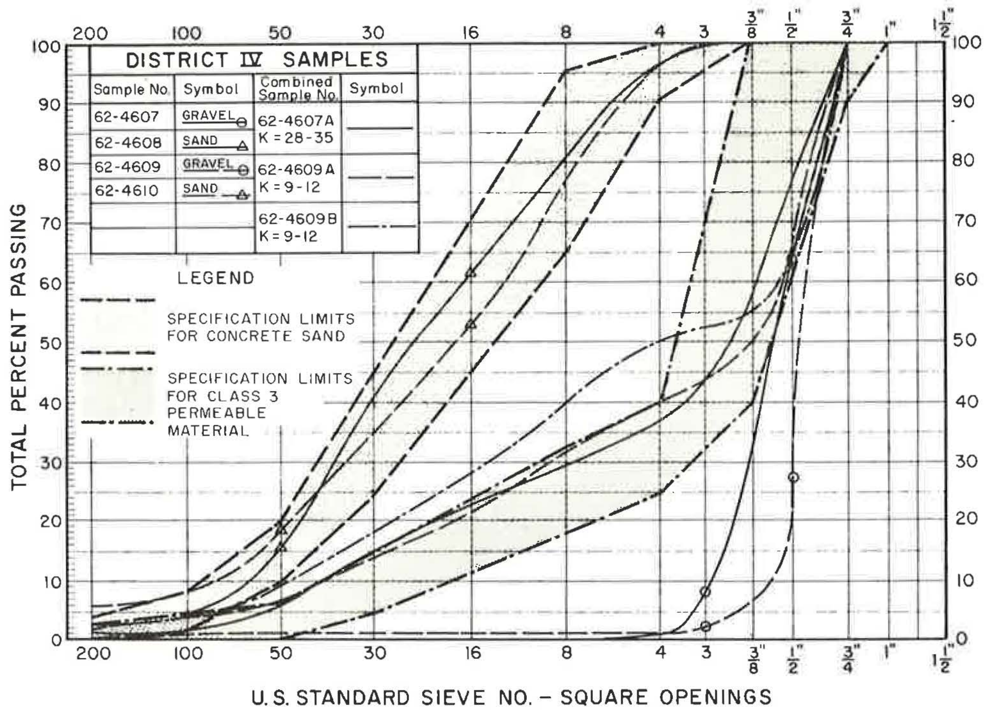

Figure 11. Grading curves for sand and gravel (additional tests).

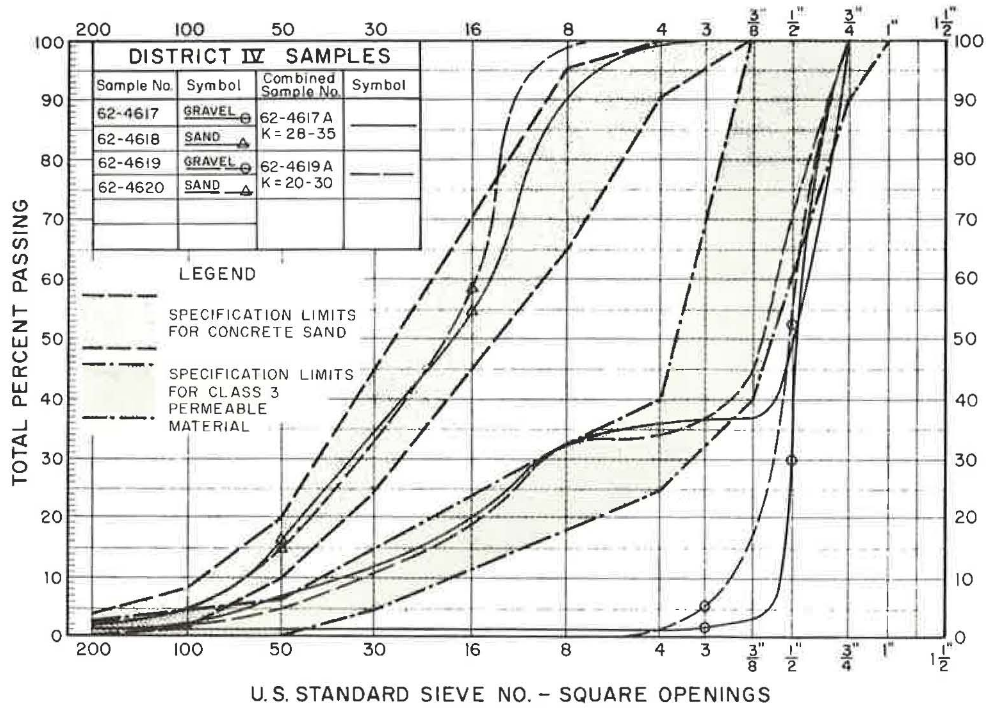

Figure 12. Grading curves for sand and gravel (additional tests).

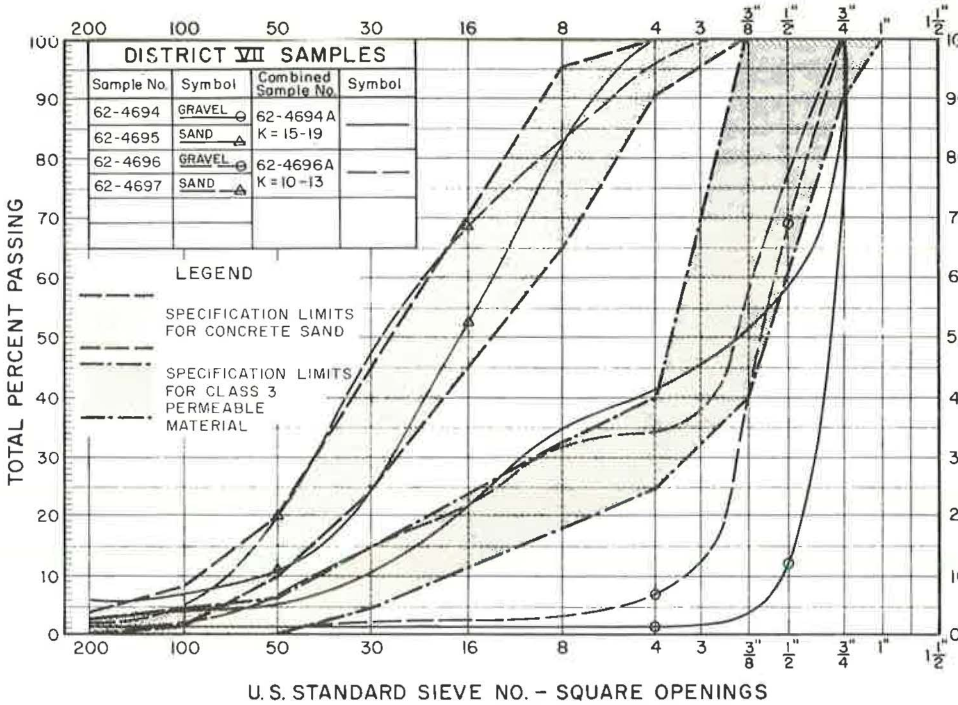

Figure 13. Grading curves for sand and gravel (additional tests).

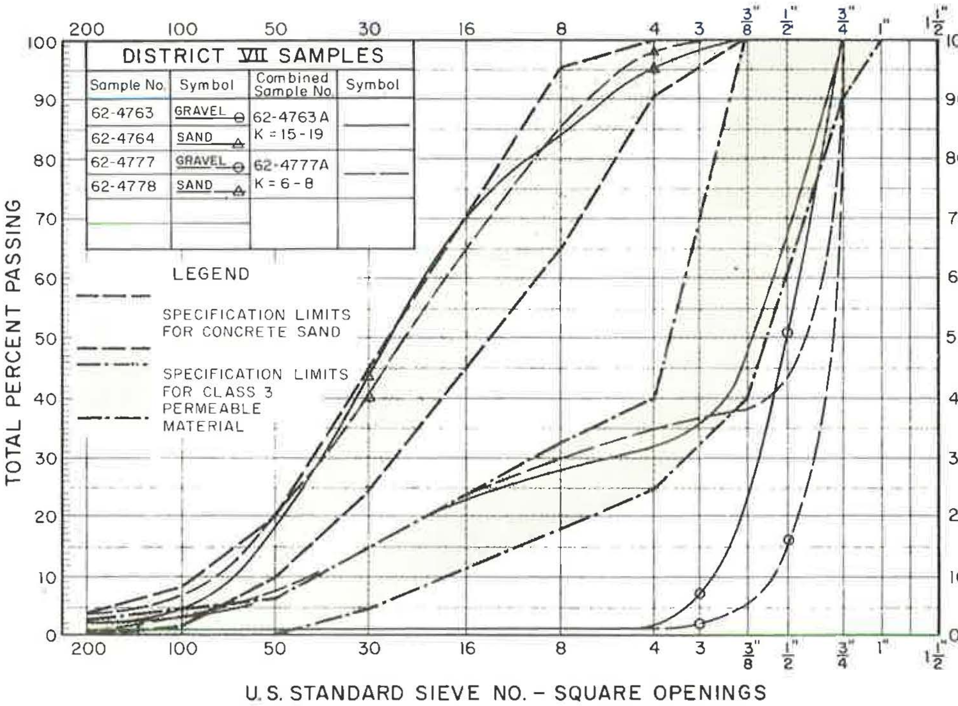

Figure 14. Grading curves for sand and gravel (additional tests).

Analysis of Test Data

Most of the test specimens had between 30 and 40 percent passing the No. 4 sieve and permeabilities ranging from 15 to 35 ft/day which is higher than for many of the graded filter aggregates previously specified. Decreasing the amount of material passing the No. 4 sieve below 40 percent increases the permeability, because mixes having less than this amount of fines tend to become undersanded. At higher amounts of fines the permeability generally falls off rapidly since there is then an excess of fines above that needed to fill the spaces between the larger aggregates, and the permeability is determined almost entirely by the grading and plasticity of the fine matrix.

The test data indicate that the materials tested have comparatively good permeabilities at maximum impact test densities less than about 132 pcf (Fig. 15), but much lower permeabilities at higher densities. Evidently at higher densities the pore spaces reduce very rapidly from rearrangements of the particles and possibly from a breakdown of particles into smaller sizes.

It has been known for many years that the permeability of aggregates and soils depends on the sizes of the pore spaces through which the water flows. In materials which have a narrow range of sizes, such as uniform sands and pea gravels, the permeability varies approximately with the square of the average grain size. Thus, $^3/_4$ in. to $^1/_2$ in. rock was found to have a permeability of 38,000 ft/day, and No. 4 to No. 8 aggregate a permeability of 8,000 ft/day. As the range of sizes in a mixture increases its permeability decreases. Mixing 80 percent of minus No. 8 to dust with 20 percent of No. 4 to No. 8 aggregate lowered the permeability from 8,000 ft/day to only 1 ft/day. The mixture contained 10 percent -200 material. The data (Table 2) showed that the permeability of graded aggregates can change very drastically with small changes in the quantity of fines.

In consideration of the above factors, it is evident that the processing and placing of graded drainage aggregates must be controlled very carefully if these aggregates are to serve the intended purpose; that is, the safe removal of water. As previously noted, when large quantities of water are anticipated it may be necessary to utilize open-graded layers of high permeability protected against soil intrusion by intervening filter layers.

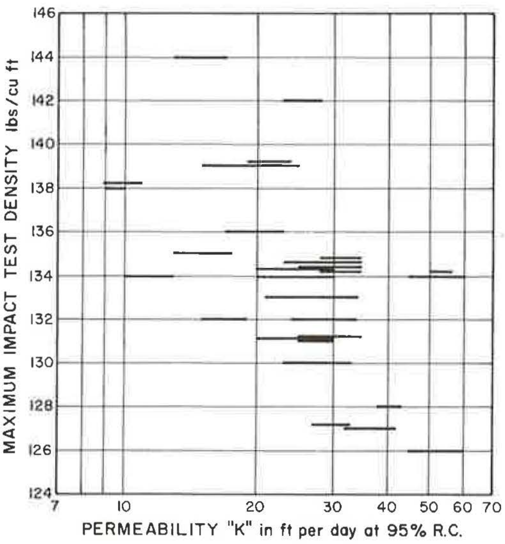

Figure 15. Permeability k vs maximum impact density.

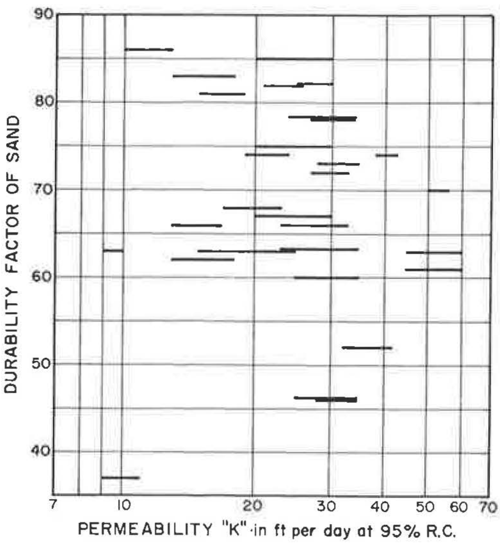

Figure 16. Durability vs permeability.

With reference to this testing program, there appears to be no relationship between the permeability and the durability factor, when the durability factor is above 40 (Fig. 16). This is probably due to the relatively high quality of the aggregates used in the tests. Only one sample had a durability factor of less than 40. The term durability factor relates to the new aggregate durability test, California No. 229.

CONCLUSIONS

In general the gradings of the blends were on the fine side of the limits of the Class 3 Standard Specials. The permeability coefficients determined by the tests average two or three times greater than those of the 1960 Standard Specifications material. In actual practice, somewhat higher permeabilities may be expected since permeability can be increased by holding the percentage of minus No. 4 to a range of 25 or 30 percent.

The use of blended mixtures permits liberal flexibility of production since a variety of aggregate gradings can be utilized. "Gap graded" blends can be avoided by adding an intermediate size aggregate. Since readily available commercial aggregates can be used, a savings in cost is anticipated over a period of time.

Care must be exercised in the handling of these undersanded mixtures to guard against segregation. Keeping the mixtures thoroughly dampened greatly minimizes segregation during placement.

It is important to emphasize that there is a need for analyzing the hydraulic conditions within drainage systems, of estimating the probable quantities of water that blankets and underdrains may be required to remove, and of designing drainage systems that are capable of doing the required job (7).

Darcy's law can be used both for estimating inflow quantities and for designing drainage systems. Charts such as Figure 1 can aid in the selection of classes of aggregates and design details that will keep structural section flooding to a minimum. Drainage is playing an important part in the design of modern highways. It is not obtained automatically. By examining accepted practices critically and being willing to experiment with new materials and methods, engineers should be able to design improved highways.

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Determination of Freezing Index Values

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Freezing index, which is used for estimating frost penetration for pavement design and for other purposes in pavement performance investigations, has been determined on a general basis for large areas of the world. However, the actual freezing index for a specific station might be very different from that estimated for the general region. The determination of freezing index for the large number of station-seasons needed to facilitate statistical treatment of data presents an overwhelming task if done by manual computing methods, and short-cut estimates reduce reliability to uselessness. There is a need for a more efficient means of determining statistically reliable values of freezing index for specific locations on a mass-production basis.

Methods of determining freezing index are described. An electronic digital computer program for finding accurate values of freezing index from daily punched card records available from the U. S. Weather Bureau and the Meteorological Branch of the Canadian Department of Transport is discussed. Problems in applying the program to the processing of masses of data are presented. Statistical treatment of the data using logarithmic-probability plotting is described for determining return period values possibly useful in application to pavement design concepts.

•COMPUTED VALUES of freezing index have provided engineers with a means of attaching numerical values to the cumulative effect of the freezing temperatures which accrue during winter seasons.

The magnitude of the value of freezing index has been correlated with the depth of frost penetration into the soil under highway and airfield pavements in areas where moderately severe winters are experienced. In this manner, freezing index has been used in pavement design procedures which take into account the factor of frost (1, 13). Freezing index is also reported in pavement performance studies as a means of documenting the severity of specific winters.

A degree day is defined as the difference between mean daily temperature and an arbitrary base temperature multiplied by the duration of one day. The base temperature of 32 F is taken when considering problems of freezing and thawing, and the degree days for any given day may be positive or negative depending on the mean temperature for that day. Degree days may be accumulated algebraically and plotted as a curve (Fig. 1). The difference between the maximum and minimum points on the cumulative curve is defined as the value of freezing index for that season.

Configurations in the cumulative degree day curve accounting for freeze-thaw cycles, and the slope of the cumulative curve have been investigated with some degree of success with regard to their correlation with pavement performance (10).

The U. S. Army Corps of Engineers in developing its use of freezing index in a pavement design method has analyzed data for wide areas of the world and determined mean values of freezing index for many stations. A value for the design freezing index may

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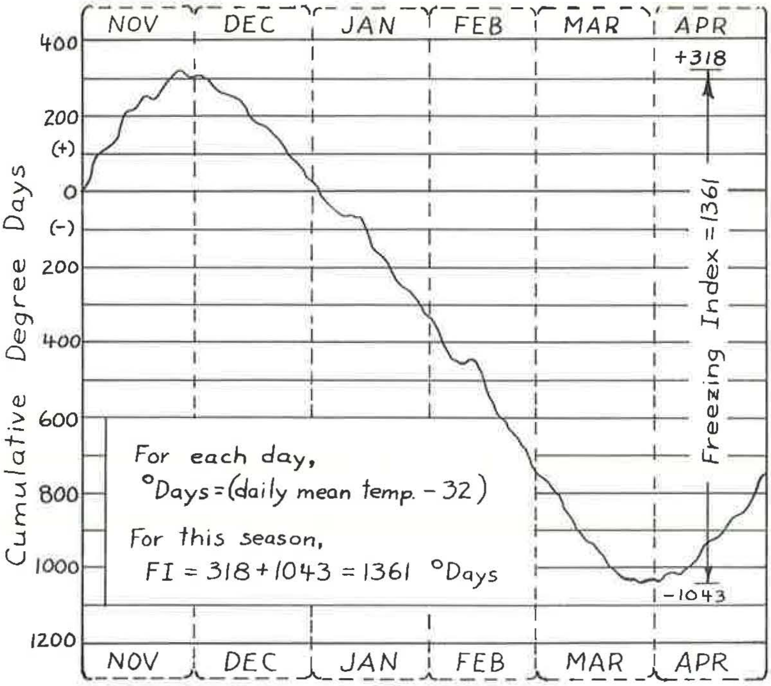

Figure 1. Determination of a freezing index value.

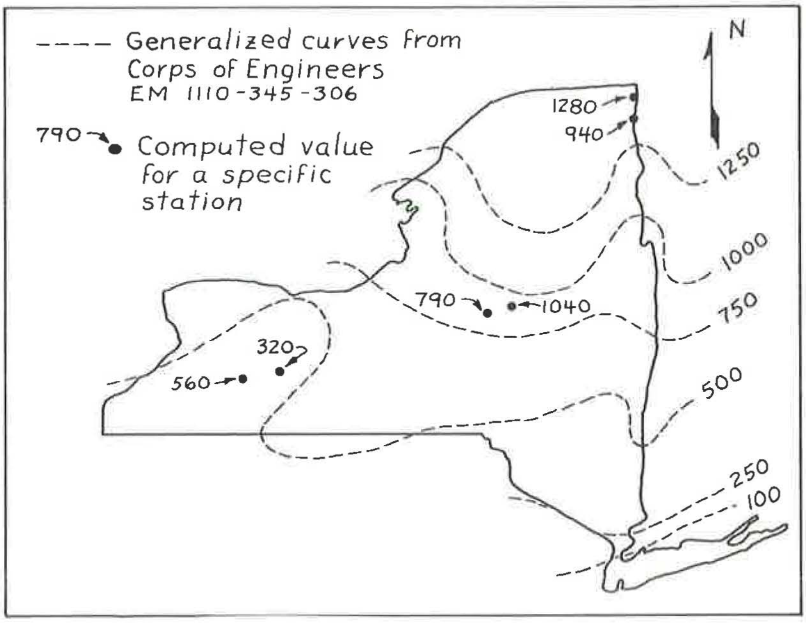

Figure 2. Mean freezing index values for New York State.

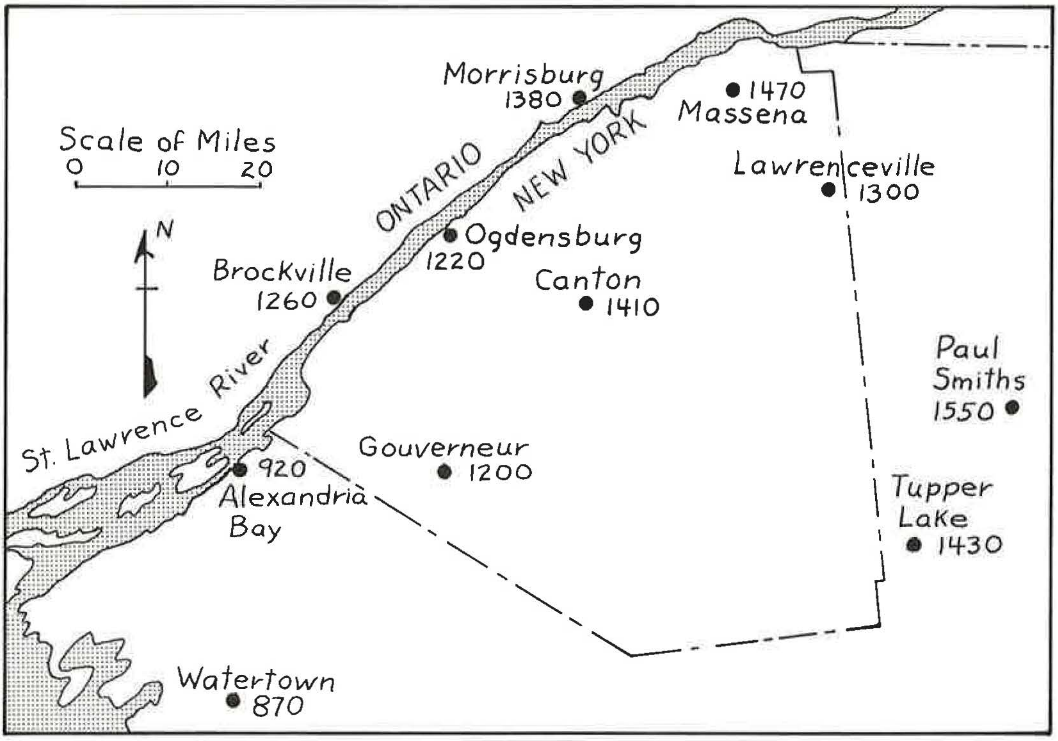

Figure 3. Mean freezing index values for St. Lawrence Co., N.Y., and surrounding area.

be found by taking the average freezing index for the three most severe winters occurring in 30 years. The value obtained is approximately equal to the 10-yr recurrence interval value.

The distribution of general values of mean freezing index as found by the Corps of Engineers (3) is shown for New York State (Fig. 2). Although general values are very useful for some purposes, it should be acknowledged that the value of freezing index for a specific location might differ greatly from the general value for the area, and that freezing index might vary widely over a small area (Figs. 2 and 3). To be applied, therefore, pavement design procedures accounting for frost penetration suggest that the design freezing index value for the specific site in question be determined (3). To be useful in very many specific design problems, therefore, a vast amount of data would have to be processed in order to make specific freezing index values for specific sites available.

The purposes of this paper are (a) to review briefly methods for computing freezing index, (b) to describe an application of an electronic digital computer to the computation of freezing indices from masses of daily weather data, and (c) to apply statistical methods to determine meaningful values of freezing index for possible applications to design problems.

GENERAL COMPARISON OF METHODS

Freezing index for a given winter season is found by computing degree day values from actual daily temperature records, and accumulating the degree days over the season beginning in fall, and ending in the spring (Fig. 4). Because the temperature records available are usually air temperature (often taken $4\frac{1}{2}$ ft above the ground), the value determined is called air freezing index (distinguished from ground freezing index).

Daily weather observations of temperature, precipitation, and other meteorological data have been recorded for a large number of stations for many years by the U. S.

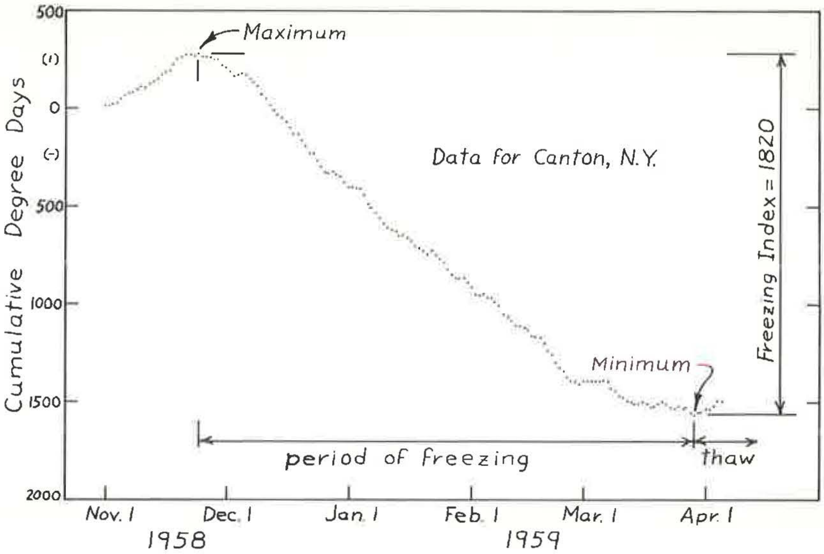

Figure 4. Determination of freezing index from daily temperature records.

Weather Bureau and the Canadian Department of Transport. Original observations which become a part of the official record are made by a relatively few first order stations and are supplemented by large numbers of individual cooperative weather observers. A variety of published summaries are issued regularly.

Manual Computation Method (Exact)

The value of freezing index for a particular season can be found by tedious manual computation beginning with tabulated records of maximum and minimum daily temperatures for the particular station as available from published weather records, such as the U. S. Weather Bureau's "Climatological Data" for state sections in monthly issues, and the Meteorological Branch of the Canadian Department of Transport's "Monthly Record." The manual process can be expedited somewhat by use of a two-man computing team. One person can mentally add the maximum and minimum daily temperatures, refer to a prepared table to find the degree day value for the day, and accumulate the values with a desk calculator. The accumulated value for each day can be called out to the second man who can tabulate and plot the points concurrently. With care given to spot checks for accuracy and allowing for necessary rest breaks, a working efficiency rate of about one manhour per freezing index determination can be achieved (Fig. 4).

The advantages of this exact manual method are as follows: (a) results are exact (by definition); (b) the plot can be used to note configurations in the cumulative degree day curve (e.g., a regularly occuring January thaw); (c) it is a convenient method for determining a few values of freezing index; and (d) it can be done using data readily available from official published records of daily temperature.

The disadvantages are that (a) the work is tedious and very boring if many seasons of data are to be processed; and (b) it is costly in manhours and is not suited to mass production of data.

Manual Computation Method (Approximate)

An approximate value for freezing index can be estimated from records of stations which experience winters with monthly mean temperatures distinctly below freezing. Values for monthly mean temperatures are often available from tabulated weather records, such as the U. S. Weather Bureau's "Climatological Data" for state sections in annual issues, and from the Meteorological Branch of the Canadian Department of

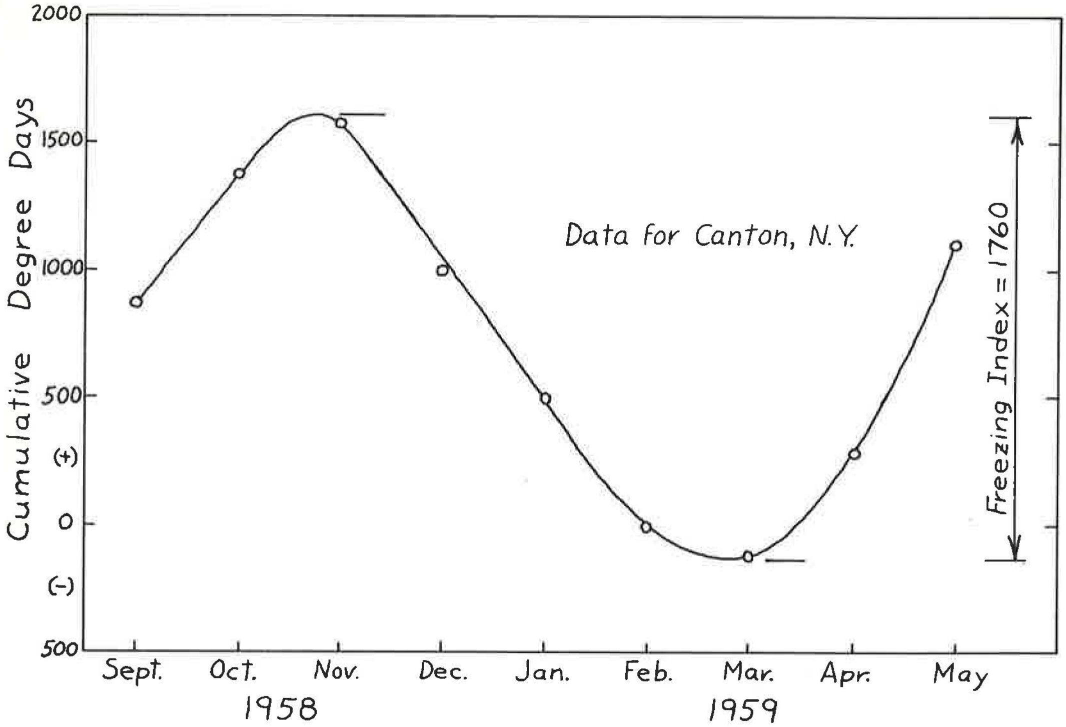

Figure 5. Determination of freezing index from monthly temperature records.

Transport's "Annual Meteorological Summary," and can be extracted for use in manually computing and plotting a rough cumulative curve (Fig. 5). The approximate value determined by this method is generally less than the exact value by an average of about 10 percent for areas with well defined winter seasons, but any given season's value might be in substantial error. The average error is less for severe winter climates. For moderate winters the error is substantially greater (10 to 40%), and it is impossible to use the method for mild winters.

The time requirement to estimate freezing index values from mean monthly temperature records is about three per manhour with reasonable care given to spot checks and efficient use of prepared data forms.

The advantages of this approximate manual method are as follows: (a) the production rate is three times the rate using daily records; (b) the method is convenient for estimating a few values; and (c) it can be done using data available from official published records of average monthly temperature.

The disadvantages are (a) the results are only approximate, and the amount of error is not known; (b) significant fluctuations in the cumulative curve during the season are masked, and often not noted; and (c) the method cannot be used for mild seasons.

Electronic-Computer Method

Because of the tedious, repetitious nature of the computations required to find freezing index, it is appropriate to consider an application of high-speed electronic digital computers to the task. Given a valid program and daily temperature data in punched card or taped form, masses of data could be processed with dispatch.

The development and use of an electronic computer were pursued because of the promise of efficiency in processing large volumes of data covering many seasons of record for scores of stations throughout a state or region (16). Quantities of values were needed before a statistical study could be made.

Beginning in 1948 and 1950, the United States and Canada, respectively, initiated major efforts to convert original observed data to punched card form in order to facilitate high speed processing of data (4). The program of conversion has been modified and developed in recent years to include film optical scanning. Current information on the status and availability of weather data in punched card and/or other form can easily be secured through correspondence.

In addition to basic sources, extensive records for selected stations are available from agricultural experiment stations at many state universities. Regional groups, such as the Regional Technical Committee for the Application of Climatology to Agriculture in the Northeast, have recently been organized in cooperation with Federal agencies to conduct a broad program of studies. Records for use in these studies extending back to about 1926 and earlier have been carefully edited and placed on punched cards and magnetic tape (6).

Editing Requirements. —Mention should be made of two essential requirements of the form of the data needed for determining freezing index from daily records by high-speed computers: complete data and chronological order. These requirements are the same as for manual computing methods. However, a lack of attention to the editing and preparation of data for the computer processing could result in inefficient and costly computer delays or invalid results which might remain undetected.

The daily temperature data for each station to be processed must be complete. Available official records occasionally are found to be incomplete for various reasons such as the inability on the part of a cooperative observer to make his observation. In editing the data, any missing temperature data must be supplied by some suitable means; e.g., estimating the temperature for the station from available values for the same date from nearby stations. If data are missing for a number of days (or weeks) the reliability of a sequence of estimated values would be open to question, and data for the entire season might better be discarded. For exacting climate studies, only those stations with reliable records extending over long periods of time should be included.

To satisfy the needs of computing, the daily records to be processed must also be arranged in chronological order. Official records are nominally reported and are published in chronological order. However, in routine processing, in including reports submitted late, and in estimating missing data, it can be expected that the required chronological order is likely to be upset. Chronological order should be checked, and if necessary, established or restored as a part of the editing and preparation of data.

Computer Program. —The IBM 1620 FORTRAN computer program is designed to perform the following operations:

1. Calculate the yearly freezing index value.
2. Determine the dates of the maximum and minimum points on the cumulative degree day curve.
3. Check to insure that the climatological data are in chronological order.
4. Check to insure that all of the climatological data used to make a determination of a freezing index value are for one and only one specific station.
5. Accumulate daily degree days for the entire year.

The computer program is adaptable to either United States or Canadian punched weather cards. Output may be either from the typewriter or from punched cards. The computer program is easily adaptable to magnetic tape facilities.*

Limitations of the Computer Program. —In order to determine the yearly freezing index value, the maximum (fall) and minimum (spring) points on the cumulative degree day curve must be clearly identified. Over many years, the winter seasons are only a small depression on the overall cumulative degree day curve. The maximum and minimum degree day points are obscured if the accumulation of degree days is begun in the summer and continued for an entire year (Fig. 6).

*A detailed description of the computer program with flow charts is available from the Highway Research Board at cost of Xerox reproduction and handling: Supplement XS-1 (Highway Research Record 68), 29 pages.

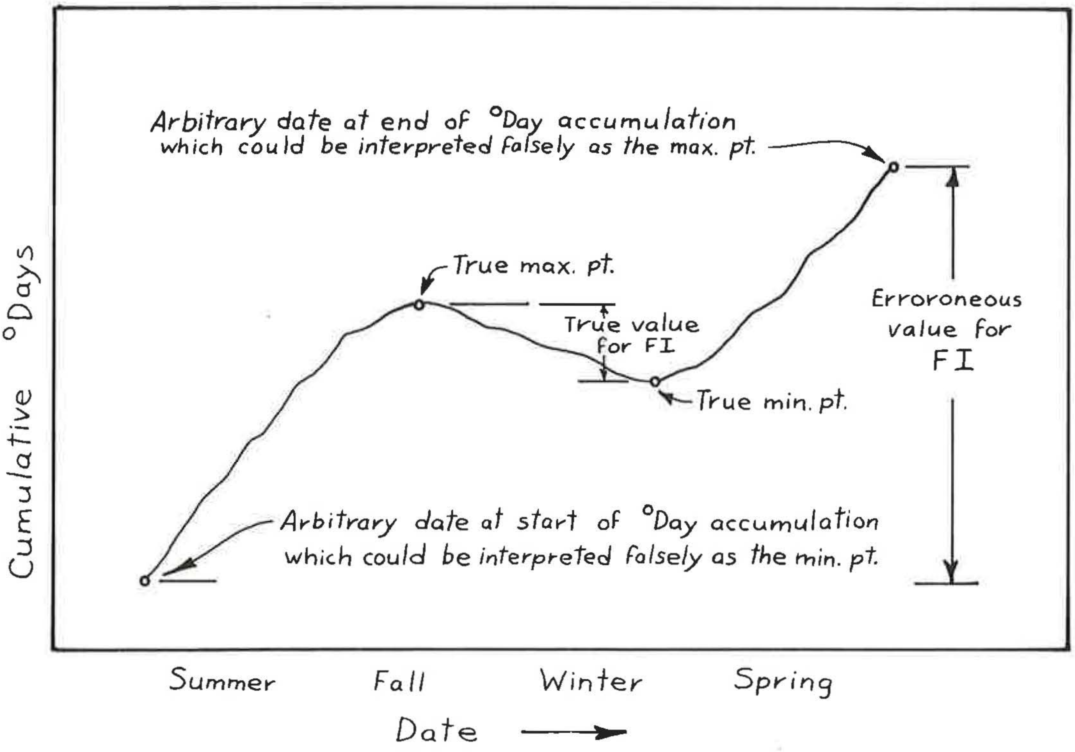

Figure 6. Effect of the incorrect selection of initial and final dates of degree day accumulation.

Thus, date restrictions are imposed to control the time of initiating and terminating the accumulation of degree days. The accumulation of degree days is reinitialized after each winter season. The restrictive dates will insure that the values on the first and last day of the cumulative degree day curve are not falsely interpreted to be the maximum and minimum degree day points. The restrictive dates define the winter seasons for the computer. These dates must be selected so that they do not obscure the maximum and minimum degree day points sought in the definition of freezing index.

The three restrictive dates are defined as follows:

1. The "initial date" must occur before the date of the maximum point. Its purpose is to initiate the degree day accumulation.
2. The "middle date" is any date between the maximum and minimum point. Its purpose is to alert the computer that the maximum point has been established and now a minimum point is to be sought.
3. The "final date" must occur after the minimum point. Its purpose is to terminate the degree day accumulation.

These three dates are illustrated in Figure 7 with example dates that can be expected to occur in a well defined winter season. The proper selection of these dates becomes a critical factor because it is necessary to estimate correctly the location of the maximum and minimum degree day points before computing the freezing index value for a station. If the restrictive dates are incorrectly defined then the resulting freezing index value is also incorrect. Errors in the selection of the restrictive dates can be determined from a scan of the tabulated results. If new restrictive dates must be selected due to an error, a rerun of the station-year is required. In areas without a well defined winter season (for example, freezing index values less than 100 degree days),

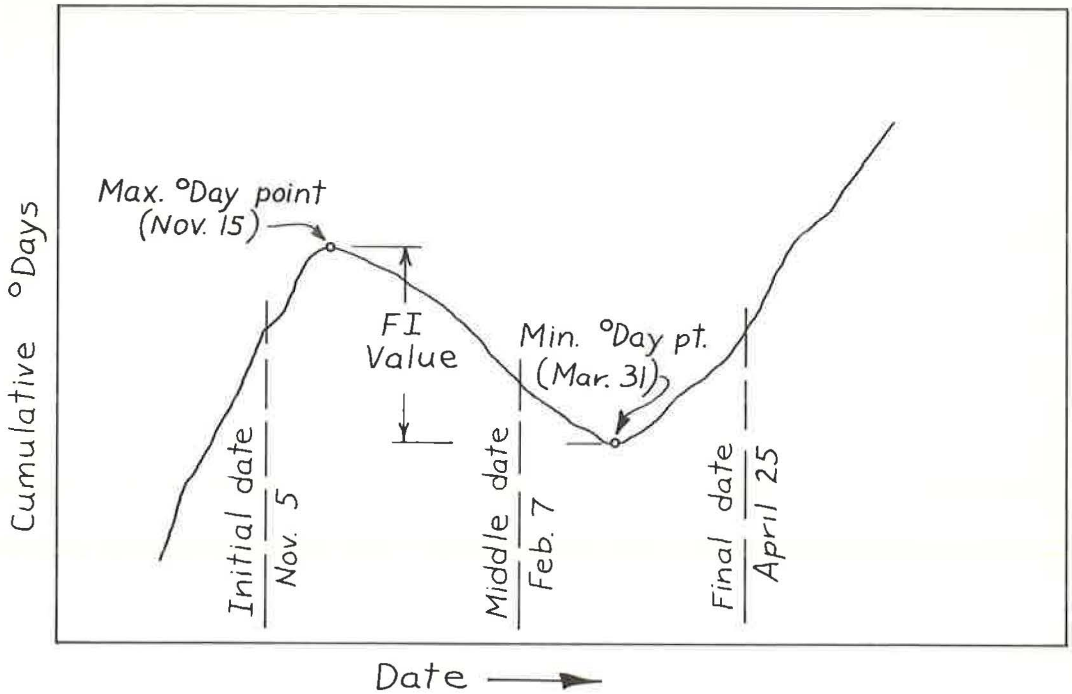

Figure 7. Examples of selected restrictive dates for computer program.

the estimation of restrictive dates becomes a serious limitation of the computer program. For these areas, the use of a sense switch will produce a daily tabulation of degree days. From this tabulation, a scan for the maximum and minimum degree day points becomes the most satisfactory way of determining the freezing index value.

A check is imposed in the program so that final cumulative degree day point never comes within five degree days of the maximum degree day point. Thus, the selection of the final degree day restrictive date is not critical. The only requirement is that the date is selected so that it insures that the minimum degree day point will be obtained prior to this date.

In milder regions the critical restrictive dates might be different from season to season, so that a new header card and reinitiation of the computer program is required.

Program modifications could be made to avoid difficulties in the application of critical dates for use on computers with sufficient storage capacities.

Evaluation of Computer Method. —The method was applied to determine approximately 900 values of freezing indices (16). In comparison with manual methods, the use of a high-speed computer in determining freezing index values has a number of advantages and disvantages. The advantages are as follows:

1. Large volumes of data can be processed efficiently at substantial savings in man-hours. About 3 minutes per freezing index determination is required in running a full year's set of daily cards through an IBM 1620 computer. Proportionately less time would be required if the summer season cards are sorted out and not used as input.
2. Mathematically accurate values of freezing index are as easy to determine as approximations.
3. Computer program has built in checks on identity on the cumulative degree day curve.
4. Use of console sense switches facilitates modifying input and output to suit needs.
5. Punched output of daily degree day accumulation could be plotted by an automatic off line plotter which would facilitate visual reading of the cumulative degree day curve.

The disadvantages are the following:

1. Use of a computer is not suited for the determination of only a few values of freezing index.

2. For most satisfactory use, the program requires that the winter be well defined (definite period of freezing weather extending for at least two weeks). Otherwise, as in the case of a mild winter, the freezing index is ill-defined. However, by use of a console sense switch, or by a trial and error procedure, borderline cases can be handled.

3. A very careful editing and preparation of input data is necessary to insure efficient processing.

For large-scale processing of winter season data in areas where freezing index is well defined, the advantages of computer processing substantially outweigh the disadvantages, and, therefore, computer use is justified.

TABLE 1

FREEZING INDEX VALUES FOR CANTON, N. Y.

Order of Occurrence		Order of Magnitude		
Winter Season (year)	Freezing Index (deg days)	Item Order No. (m)	Freezing Index[a] (deg days)	Frequency[b] (%)
1922-23	2040	1	2290	2.56
1923-24	1280	2	2040	5.13
1924-25	1460	3	1910	7.69
1925-26	1800	4	1850	10.26
1926-27	1470	5	1820	12.82
1927-28	1300	6	1800	15.38
1928-29	1170	7	1780	17.95
1929-30	1430	8	1740	20.51
1930-31	1300	9	1730	23.08
1931-32	950	10	1680	25.64
1932-33	800	11	1660	28.21
1933-34	2290	12	1540	30.77
1934-35	1780	13	1510	33.33
1935-36	1740	14	1480	35.90
1936-37	1050	15	1470	38.46
1937-38	1440	16	1460	41.03
1938-39	1480	17	1440	43.59
1939-40	1910	18	1430	46.15
1940-41	1680	19	1430	48.72
1941-42	1290	20	1430	51.28
1942-43	1730	21	1360	53.85
1943-44	1430	22	1300	56.41
1944-45	1660	23	1300	58.97
1945-46	1510	24	1290	61.54
1946-47	1220	25	1280	64.10
1947-48	1850	26	1250	66.67
1948-49	880	27	1220	69.23
1949-50	1250	28	1170	71.79
1950-51	1060	29	1170	74.36
1951-52	1060	30	1060	76.92
1952-53	740	31	1060	79.49
1953-54	960	32	1050	82.05
1954-55	1360	33	980	84.62
1955-56	1540	34	960	87.18
1956-57	1170	35	950	89.74
1957-58	980	36	880	92.31
1958-59	1820	37	800	94.87
1959-60	1420	38	740	97.44

[a] In order of decreasing magnitude.
[b] At which given value was equaled or exceeded.

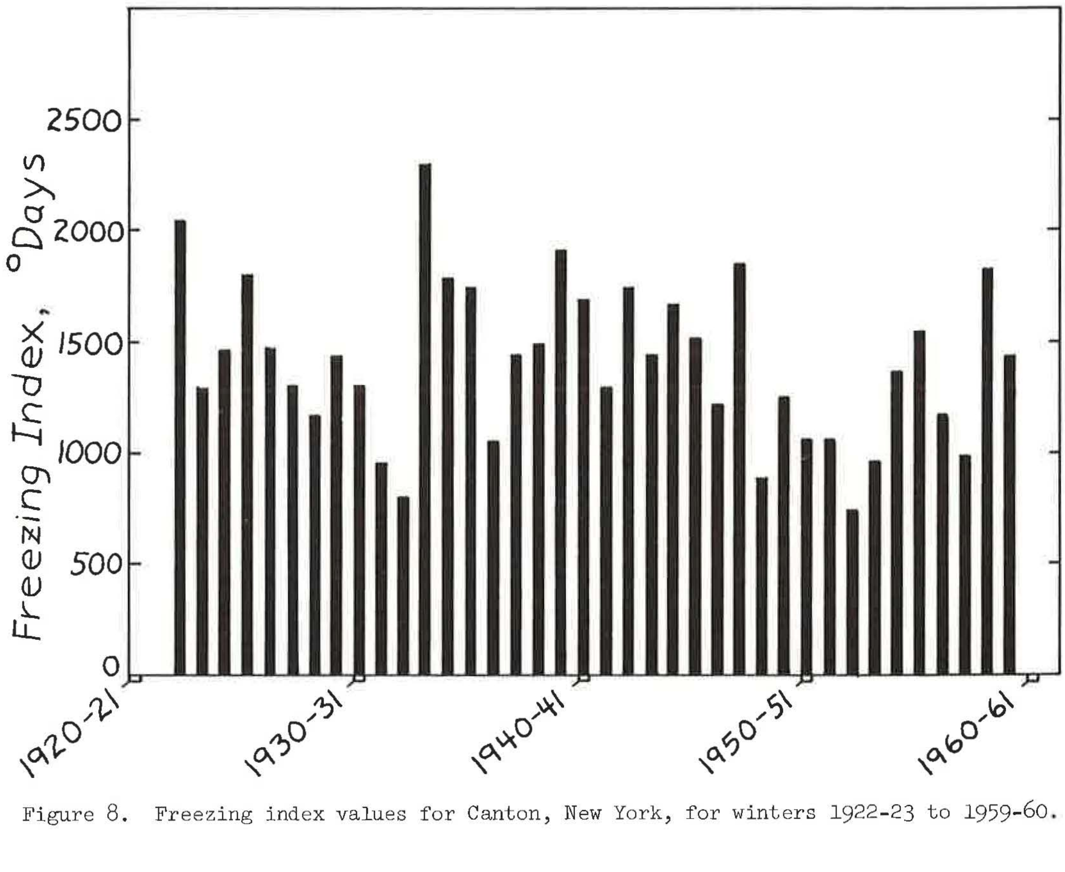

Figure 8. Freezing index values for Canton, New York, for winters 1922-23 to 1959-60.

OBTAINING A MEANINGFUL DESIGN VALUE OF FREEZING INDEX

With natural fluctuations in climate the values of freezing index vary widely for a given location from season to season, as given in Table 1 and shown in Figure 8 for Canton, N. Y. Values available for the winter of 1922-23 through 1959-60 range from a minimum of 740 occurring in 1952-53, to a maximum of 2290 in 1933-34. The average of all 38 seasons is 1403 degree days.

Acknowledging the existence of widely fluctuating values of freezing index, the question remains as to what value might be selected for applications to design. A mean value of freezing index does not account for the occurrence of the more severe winters of special concern. The extreme value for a period of study might be too conservative and/or unreliable. Linell (12) in discussing this matter suggested that a more significant design freezing index value would be that which occurs about one year in ten, particularly in areas of low mean freezing index. This design value can be approximated by computing the average air freezing index of the three coldest winters in the latest 30 years of record and is the current design practice of the Corps of Engineers (3, 13). However, it has been found that there is only a fair correlation between mean winter season temperatures and freezing index computed from daily records (15). At least five or six coldest seasons must be selected for computing freezing indices to be sure of finding the highest three values which could be averaged for use in design.

Return Period Value for Design

As experience is gained and refinements are made in engineering practice, more attention can be paid to bringing in considerations based on calculated risk. Concepts of design life are based on this approach, although as applied to pavement designs allowing for climate effects a designer must depend on his experience and judgment in estimating the risks involved. Although neither the only factor nor the most important factor, it is suggested that return period values of freezing index might be worthy of further consideration in future refinements in design methods accounting for seasonal frost. If there is justification in pavement design procedures to include the factor of freezing index to account for frost penetration, there is justification to refine freezing indices to more accurate and statistically reliable values.

A return period value is one which is expected, on the average, to be equaled or exceeded only once in a stated interval. It is particularly useful in describing naturally occurring phenomena which appear to fluctuate widely by chance. For example, after an analysis of data for Canton, N. Y., it can be stated that a freezing index value of 1950 is expected, on the average, to be equaled or exceeded only once in ten years, a value of 2100 only once in 20 years, and a value of 2260 only once in 50 years. The stated values are not to be interpreted as forecasts for a certain time, but rather they are the most probable largest values to occur within the time periods stated.

Determining Return Period Values

Although other and more sophisticated statistical methods can be applied in computing the probabilities of the occurrence of a certain value, the relatively simple graphical method using probability paper for analyzing return period values for stream flows under flood and drought conditions is of special interest (7, 8). An example of probability paper is shown in Figure 9. With some modification, this method is used widely today in the field of hydrology. Mockus (14) discussed this concept and method of determining a flood frequency value. Burchinal and Dickerson (2) apply the method in determining rainfall probability. It can be adapted directly for use in freezing index analysis, as by Legget and Crawford (11). In applying the graphical method, it is desirable to have at least 30 points for each station, but with the application of electronic computation, the quantities of data necessary would be readily available for use.

Example Determination

Recent developments in the theory of extreme values, such as reported by Gumbel (5), could have been applied to the problem at hand. However, for present purposes,

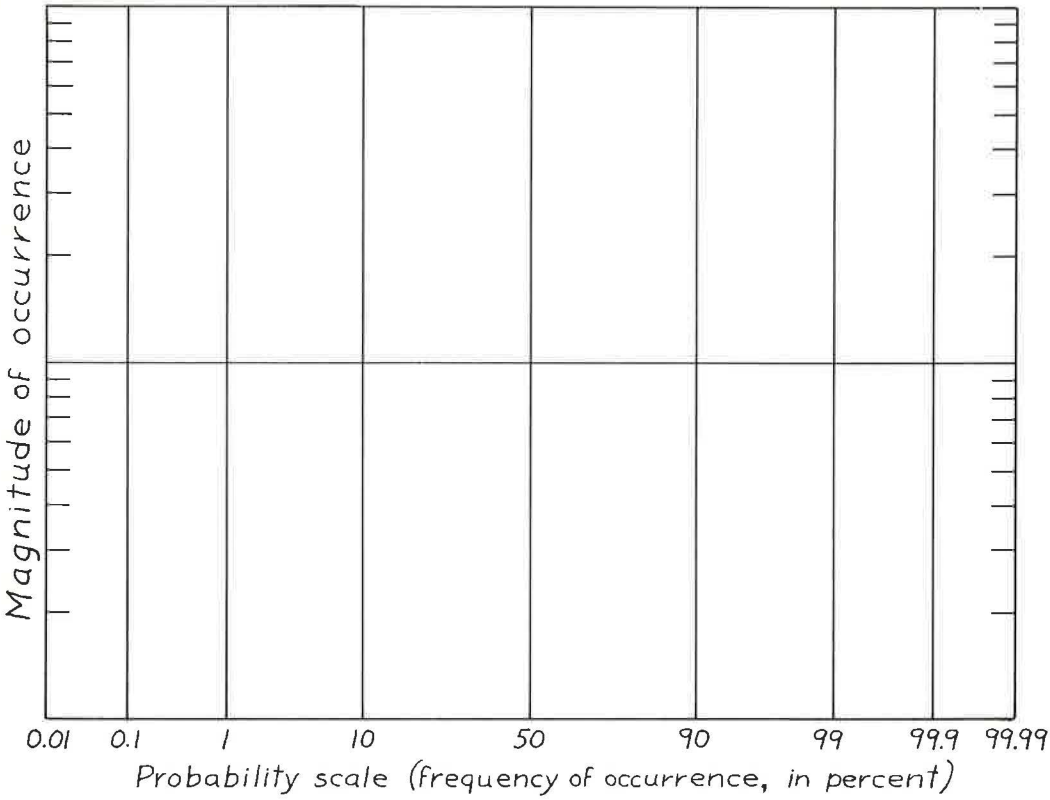

Figure 9. Sample of probability paper.

it is sufficient to illustrate the point by using a relatively simple plot of data on logarithmic-probability paper to determine return period values of freezing index for Canton, N. Y. The data for the 38 seasons are placed in order of magnitude (Table 1), and then the frequency at which a given value was equaled or exceeded is computed. In the example, the Kimball method (9) is applied to compute frequencies, although other methods would yield very similar results. The frequency is found from

$$F = \left(\frac{m}{n + 1}\right) 100 \qquad (1)$$

in which

- m = the order number;
- n = the total number of items; and
- F = the percent of years during which the freezing index is equal to or greater than the freezing index of the order item m.

The computed frequencies are the plotting positions on a probability scale (percent) as the abscissa and with freezing index on the ordinate. In the example (Fig. 10), a line of best fit is drawn by eye through the plotted points. The equation of the line could be found and tests for goodness of fit could be made, but in practical application, for purposes at hand, these steps are not necessary and might even be misleading if not properly applied.

Probability paper of this type is available commercially with ordinates laid out both in logarithmic and arithmetic scales. The choice would depend on how the data plotted;

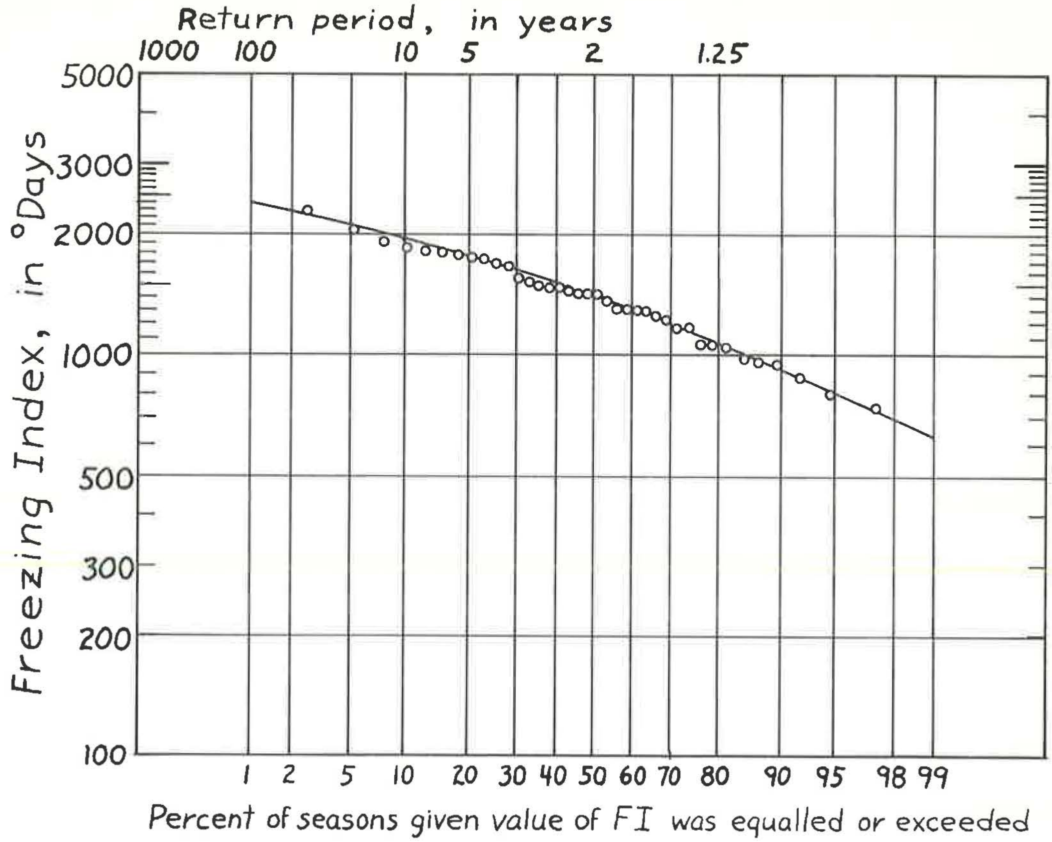

Figure 10. Logarithmic probability plot of freezing index data for Canton, New York, for winters 1922-23 to 1959-60.

it is desirable for the plot to be as nearly a straight line as might be convenient to facilitate drawing the line of best fit by eye in practical application. Values should be selected from near the upper end of the line which represents the more severe winters, but curve extrapolation should be done with caution as to reliability.

Given a plot such as Figure 10, it is possible to select frequency values for any return period within reasonable limits of the data.

As with any study of historical events, the analysis depends on what has happened in the past. From the analysis of past records, it can be stated, for example, that a freezing index value of 2100 had a return period of 20 years corresponding to a frequency of 5 percent. The assumption is made that, unless strong evidence of climate change can dictate otherwise, it is probable that a freezing index of 2100 or greater will occur at Canton sometime during the coming 20-yr period. Values for any other return period can similarly be found from Figure 10, although extrapolation beyond 40 years for the data available would be less certain as to reliability.

The plot of data would also be useful in comparing a given season's freezing index with the general distribution. For example, if a given season produced a freezing index of 1830, it can be said that a value of at least this magnitude is expected to occur within any 7-yr period.

The lower end of the curve might be equally useful in other applications. For example, at the lower end there is a 98 percent probability that the freezing index will be equal to or greater than a value of 700, or a value less than 700 will probably not occur more than once in a 50-yr period.

Choice of Return Period Value

The choice of the proper return period for design purposes is beyond the scope of the present paper but is a subject which might be worthy of further study. An understanding of climate effects on pavement performance is far from complete, and design procedures remain arbitrary in the manner of considering the effects of certain factors, such as soil and frost penetration. The factor of frost penetration alone can be estimated from freezing index which is easily computed, and a freezing index value with a return period corresponding to the design life of the pavement might prove to be the proper value to select.

Additional Applications

In addition to the application of return period values of freezing index, it is suggested that the concept of frequency of occurrence and return period values might also find useful application in studying other factors considered important in frost action studies. For example, soil moisture of different layers in and beneath the pavement vary considerably as precipitation and drainage conditions change. Accurate measures of soil moisture could be analyzed to account for the frequency and return period values. Also, temperature gradients within the soil vary widely over the season as air-temperatures vary. Accurate measures of the changes in slope of the temperature gradient could be analyzed to account for the frequency and return values. The growth of ice lenses in frost susceptible soil depends on the combination of freezing temperatures and available moisture, and possibly an analysis of the expected frequency of certain temperature gradients and soil moisture would contribute to a better understanding of frost action. The time unit for an analysis of frequency need not be one year, as in the case of the freezing index example, but can be any appropriate unit, such as an hour or a day. An intensive study of soil moisture and temperature gradients or any other factors, of course, would depend on an ample supply of reliable data.

CONCLUSION

Two principal conclusions were drawn: (a) the electronic digital computer program and method presented can be used efficiently to process large quantities of daily weather records in determining accurate values of freezing indices; and (b) given large quantities of results, the application of probability paper can produce meaningful values for possible use in design.

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Cooperation and assistance was received from the Department of Civil Engineering, Clarkson College of Technology. The following individuals were especially helpful: Professor Robert D. Larsson, for initial program concepts; Dr. John M. Perry, Director of the Computing Center, for initial program development; Mr. William G. Austin, for manual computations in early stages of development; Mrs. Anne Serabian, for manuscript typing; and Mrs. Betty Lyman, for duplication of masters.

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Soil Suction Effects on Partial Soil Freezing

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The ability of water to move in soils under temperature, concentration, pressure or other gradients, is dependent to a great extent on the particle interaction characteristics of the soil-water system. In both saturated and unsaturated soils, the total effect of such interaction may be measured and described in terms of soil suction (pF) or moisture potential. This potential of water can be a convenient tool since it may be used without specifying exactly the nature of the forces holding water to soils.

This paper presents measurements of soil suction and relates them to the partial freezing phenomenon of three soil types—a kaolinitic clay, a medium feldspar quartz clay, and a silt. Over the range of temperatures considered (from 0 C to -16 C), it was shown that the quantity of water remaining unfrozen may be related directly to the soil suction parameter.

The importance of freezing or thawing history may be noted in the difference in quantity or percentage of water remaining unfrozen, depending upon whether the test samples were frozen to the test temperature or thawed to the test temperature from a previous lower temperature. As example, for the medium clay at a pF of 3.11 and at -0.5 C, the unfrozen water content dropped from 38.1 percent for samples frozen to the test temperature, to 21.5 percent for others thawed from a lower temperature to the test temperature of -0.5 C. At -16 C, the drop was from 9.5 to 7.2 percent for the same condition. At a pF of 3.79 and at -16 C, the drop was from 7.4 to 5.4 percent.

The pF parameter and partial soil freezing relationships are shown and discussed for the three soils studied. In all cases, the results show that the higher the pF value (measured at room temperature), the greater is the percentage of water remaining unfrozen at any subfreezing temperature. In terms of surface tension forces and interaction of long- and short-range forces (Gouy forces) a lowering of the temperature would increase the former and decrease the latter.

A simplified pressure-membrane technique for soil suction measurements is presented which would allow for routine soil suction determinations.

•IN a given soil-water system, soil moisture movement occurs as a result of a variety of causes, including temperature, concentration, pressure, and other physical and chemical gradients. In both saturated and unsaturated soils, the ability of water to move is to a large extent dependent on the water holding capacity of the soil. The factors which influence the forces holding water to soil are not well known or clearly understood. Low (1) suggests that both movement and equilibrium of water in soil-water systems are affected by soil and clay-water forces. In general, measurements of soil suction expressed in pF units (2) or as moisture potential serve to provide a useful understanding of moisture retention, which in turn gives an indication of the interaction characteristics of the soil-water system. This includes menisci or capillarity effects and interaction of the long- and short-range forces in the system. The moisture potential, or specifically the soil moisture potential may be defined as the energy or amount of work required to move a unit mass of water from a position within a soil mass to a free water surface.

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Since many of the problems arising in the determination of properties and characteristics of soils are in part dependent upon soil moisture relationships, it becomes necessary to investigate soil suction in terms of basic soil parameters. The purpose of this study is to establish these relationships with initial application to the understanding of the role of moisture potential or pF in partial soil freezing. A secondary purpose is the design and development of simplified equipment and techniques which would allow greater flexibility in the measurement of pF in general.

In previous studies on soil freezing (3, 4, 5), it has been established that total freezing of pore water is not often realized. The results show that the quantity of soil-water remaining unfrozen varies with factors such as temperature, soil composition, and initial water content. It is suggested (6, 7, 8) that unfrozen water in partially frozen soils (the term "partially frozen soils" is used to indicate incomplete freezing of the fluid phase) is dependent to a great extent on the interaction characteristics of the particular soil-water system. If one accepts the thesis that the interaction characteristics of a soil-water system are a function of soil composition, configuration, matric potential and interparticle forces (and there is an overwhelming body of studies to indicate that this is so), then it seems reasonable to expect that a measure of this interaction (specifically moisture potential or pF) may be used to describe relationships between original water content and unfrozen water content for any subfreezing temperature. Hence with the indication that forces holding water to soil play a distinct role in the determination of partial soil freezing, then moisture potential or pF measurements could provide a useful understanding of unfrozen water content and subfreezing temperature relationships.

EXPERIMENTAL TECHNIQUES AND PROCEDURES

pF Measurement Techniques

Various methods for soil suction measurement have been and are now in use. Many of these are suitable only for limited pressure or suction ranges and suffer from other limitations and constraints. A detailed evaluation of these techniques has been presented by Croney and Coleman (9) and will not be repeated here. In general the methods and ranges of pF capacity are given in Table 1.

Other methods available for the measurement of soil suction include: (a) continuous flow—variation of suction plate; (b) rapid method—variation of continuous method; (c) pressure plate—another variation of suction plate; (d) oedometer method; (e) vacuum desiccator—similar to balance sorption; and (f) electrical resistance gages.

The method used for this study was based on the pressure-membrane technique since this gives capacities ranging from 0 to at least 6.2 pF units (9). However, instead of a pressure piston arrangement where compressed air is introduced through a point and further actuated by the piston, the device used in this particular study essentially simplifies both pressure application and measurement systems.

Figure 1 is a schematic picture of the experimental technique. Figure 2 shows the details of the sample chamber. The principle of applied pressure as used in this study is more readily explained with the aid of Figure 3. If a soil sample is sufficiently thin to prevent moisture migration due to pressure consolidation, water will leave the sample until the sum of the surface tension forces and forces due to interaction of interparticle forces develop a suction pressure equivalent to the applied pressure. The ceramic filter at the bottom end of the test cell, of high known air entry value, insures the presence of a free water table adjacent to the soil sample. Schofield (2) suggested that the air pressure technique could be used if suitable filters could be provided.

After placing the test cell with the prepared sample in the pressure-membrane

TABLE 1

METHODS AND RANGES OF pF CAPACITY

Method	pF
Tensiometer	0 - 2.9
Direct suction	0 - 3.0
Suction plate	0 - 3.0
Centrifuge	3.0 - 4.5
Sorption balance	5.0 - 7.0
Freezing point depression	3.0 - 4.5
Pressure membrane	0 - 6.2

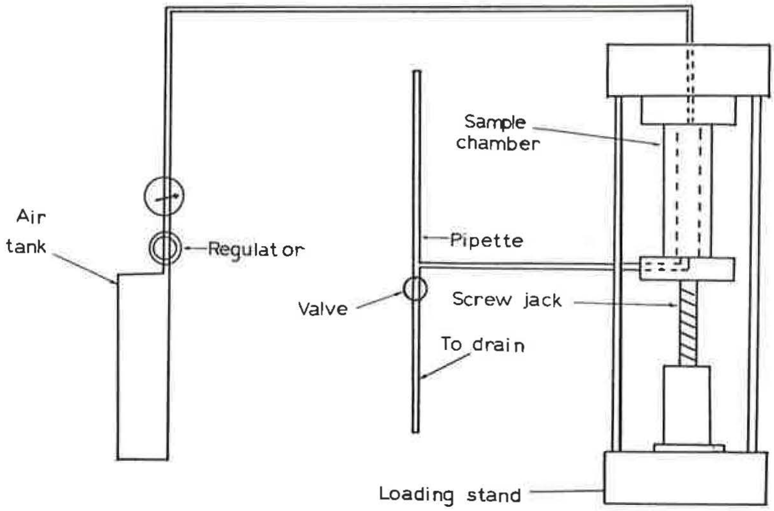

Figure 1. Soil suction apparatus.

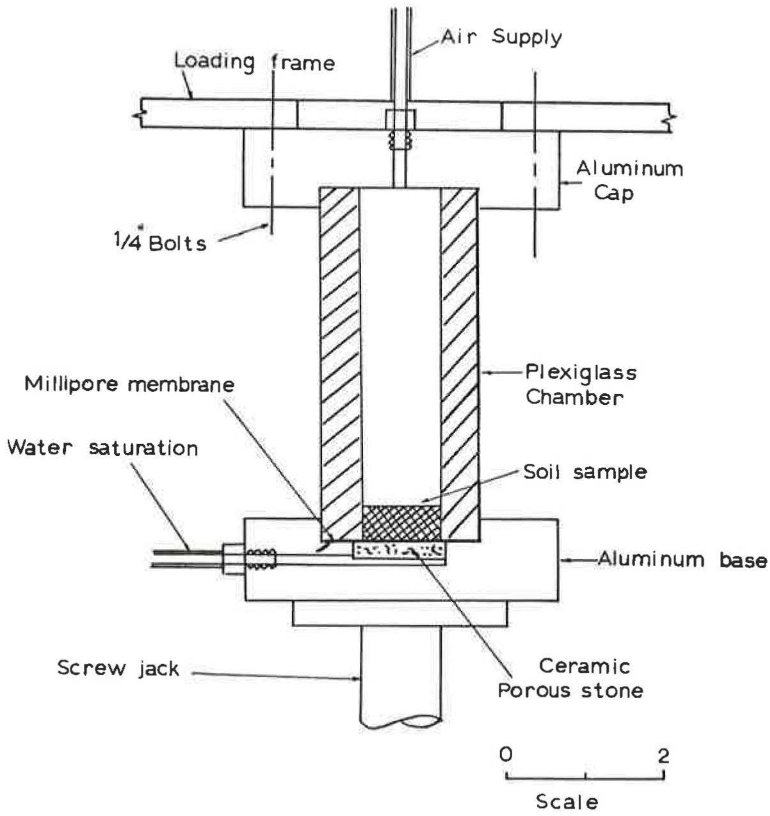

Figure 2. Cross-section of sample chamber.

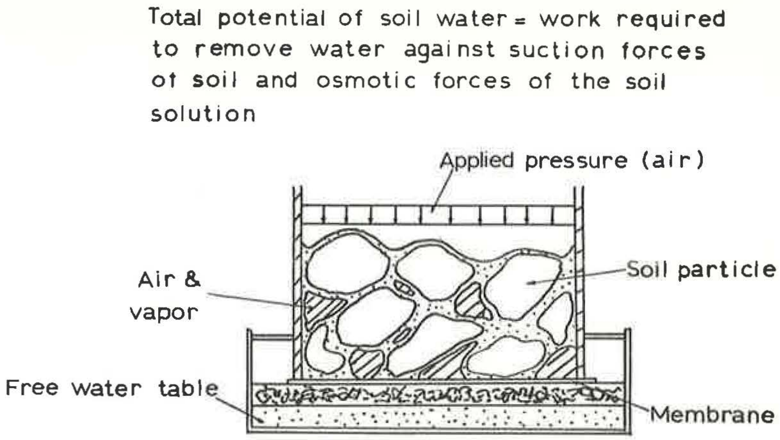

Figure 3. Principle of applied pressure.

TABLE 2

SOIL PROPERTIES AND CHARACTERISTICS

Consistency	Plastic Clay	Medium Clay	Silt
Liquid limit	74	67	25.1
Plastic limit	31	28.8	17.0
Specific gravity	2.75	2.73	2.68
Grain size (by weight), % finer:			
0.15 mm	100	100	100
0.10 mm	100	100	93
0.05 mm	100	91	83
0.01 mm	100	72	22
0.005 mm	100	66	2
0.002 mm	100	30	0
0.0008 mm	80	0	0
0.0005 mm	67	0	0

system, a free standing head of water is introduced on top of the specimen in the cell. The application of air pressure to the water forces water through the soil-water system and with time, equilibrium is reached—signified by no further extrusion of water from the system. The total soil moisture stress is then expressible as the moisture potential or soil suction since the applied air pressure is known and the residual water content can be determined. Since the moisture potential represents the total soil moisture stress of the soil-water system (i.e., the suction or pressure necessary to extract moisture from the soil-water system for a particular configuration), it can readily be seen that it is possible to derive the relationship for moisture potential as a function of water content for a particular soil.

Sample Preparation and Unfrozen Water Content Determination

The soils used were a plastic kaolinite clay, a medium feldspar quartz clay and a clayey silt, the physical properties of which are given in Table 2.

X-ray diffraction analyses showed that the predominant mineral for the silt was quartz with traces of feldspar. In the case of the medium clay, both feldspar and quartz were registered together with trace fractions of chlorite, biotite and amphibole. The plastic kaolinitic clay (Bell clay) was first procured as a kaolin clay. However with subsequent use, it became evident that the expected performance was being obscured. The x-ray diffraction pattern showed the kaolinite peaks but also registered trace fractions of degraded kaolinite, chlorite, flour-apatite and quartz. It would seem that the degraded kaolinite with properties not unlike amorphous materials has subverted to some extent the normal behavior pattern of the kaolinite.

To arrive at varying particle orientation and densities for the determination of percent unfrozen water the test samples were either compacted in a molding cell or consolidated from a slurry. These prepared samples were subsequently wrapped in wax paper following extrusion from the cells and stored in a freezer for a 72-hr period. The frozen samples were not completely saturated, as is evident from the method of sample preparation. This procedure seemed necessary if variations in total moisture stress were desired, consistent with a constant compactive effort. The calorimetric method was used to arrive at the quantity of water remaining unfrozen at the desired test temperature.

RESULTS

Soil Suction

Figures 4 and 5 show the relationship between soil suction and water content at room temperature. Initially, all the soils tested for soil suction were compacted in the molding cell with a spring tamper adjusted to provide approximately 3-psi compactive pressure. Soil suction or moisture potential for samples compacted in this manner are designated as "medium compacted."

Resultant consolidation or compression of the medium compacted samples arising from the air over-pressure in this pressure membrane technique is negligible at low pressures and insignificant at the higher pressures. To provide a better understanding of configuration or particle orientation effects on soil suction, both the kaolinitic clay (Bell clay) and silt soils were also used in initial slurry form, i. e., slurry samples were used for soil suction measurements. Corresponding results for these samples are shown together with the medium compacted samples. In initial slurry form, equilibrium moisture retention under any applied air over-pressure was reached only after some degree of consolidation or compaction had occurred because of the applied pressure.

As expected, silt slurry samples produced lower values for moisture potential at corresponding water contents in comparison with medium compacted samples. The greater degree of scattering for the silt slurry samples would suggest a high random reorientation in resultant compression or consolidation. In the plastic Bell clay, although it may not be immediately evident why the slurry samples have higher moisture potentials or soil suction values at corresponding water contents when compared to the same samples prepared with the spring tamper, the answer may be found in the final reorientated or equilibrium structure of the initial slurry samples. The water holding capacity of clay samples compacted statically (as may be visualized by the air over-pressure) is higher than those compacted with a spring tamper.

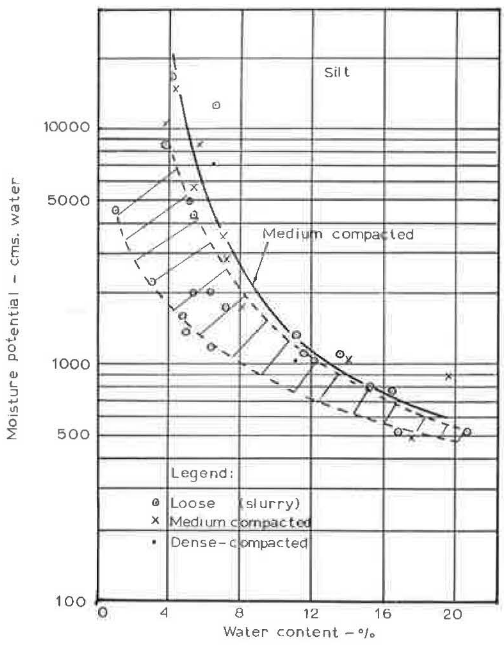

Figure 4. Moisture potential and water content.

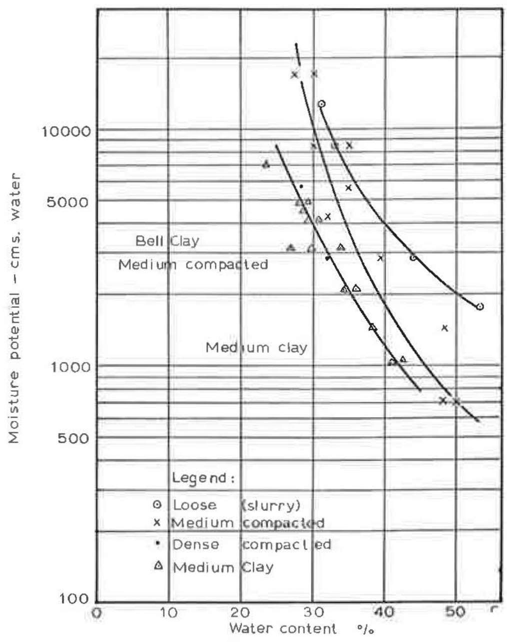

Figure 5. Moisture potential and water content.

As anticipated and indicated in previous research, pF or moisture potential decreases with increasing water content. The relationship is not necessarily linear. On the basis of forces of interaction, it is expected that lower water contents would give rise to a higher interaction characteristic between particles presuming that the degree of saturation is maintained. Again, the interaction characteristics include matric and osmotic potentials. This may be verified by examining the swelling and shrinkage characteristics of such soils.

Proceeding along this line of reasoning, it follows that the ability to freeze soil water must be dependent upon the facility for freezing of water within soil voids wherein interaction occurs. The greater the intensity of interaction, it would necessarily seem that the lower must be the temperature needed to freeze the pore water. Schofield (2) suggests that the free energy difference (measured in terms of pF or as moisture potential) may be related directly to the freezing point depression. To avoid possible confusion, the moisture potential or soil suction referred to in this paper concerns measurements made at room temperature. Moisture potential dependency on subfreezing temperature is recognized and discussed in a later section, however the relationships shown and discussed herein concern themselves solely with moisture potentials at room temperature.

Quantity of Water Remaining Unfrozen

Figures 6 through 9 show the quantity of water remaining unfrozen for the silt and medium clay soils in terms of initial water content, or percent saturation. Unfrozen water content (i.e., ratio of the weight of water remaining unfrozen and the weight of mineral particles expressed as a percentage) has been related to the original water content (Fig. 6). Because of the difficulty in exact duplication of soil samples and configuration before and after freezing, the values plotted showed some scatter which have been encompassed by upper and lower bounds. The bands shown, which encompass the test values derived, also include the effect of freezing or thawing to the test temperature. It is perhaps unfortunate that both scatter and hysteresis tend to overlap here. The upper boundary represents test results obtained for samples frozen to the test temperature as designated, and the lower boundary indicates those results obtained for samples thawed to the same test temperature. It might be argued that the exact positioning of the boundaries is affected by the scatter. However it cannot be denied that the differences in freeze-thaw are sufficiently marked to define cause and effect. What might be agreed upon is that qualitatively these bands are useful to show the freeze-thaw effect, but do not necessarily quantify this effect precisely.

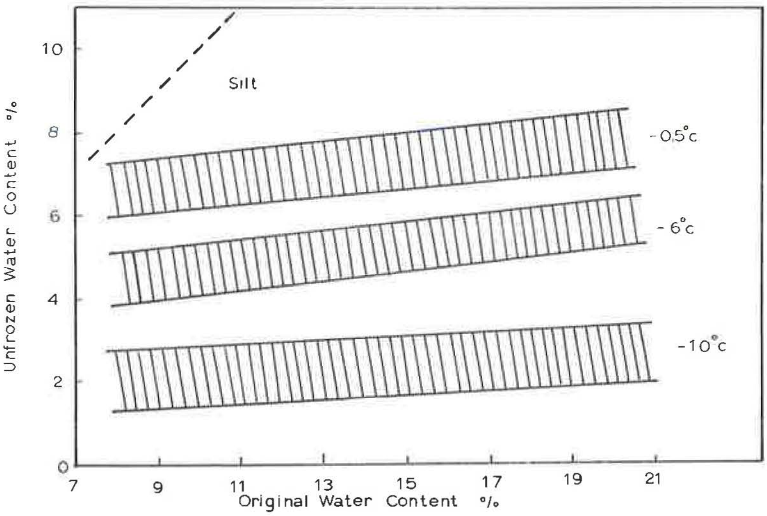

Figure 6. Unfrozen water content and original water content.

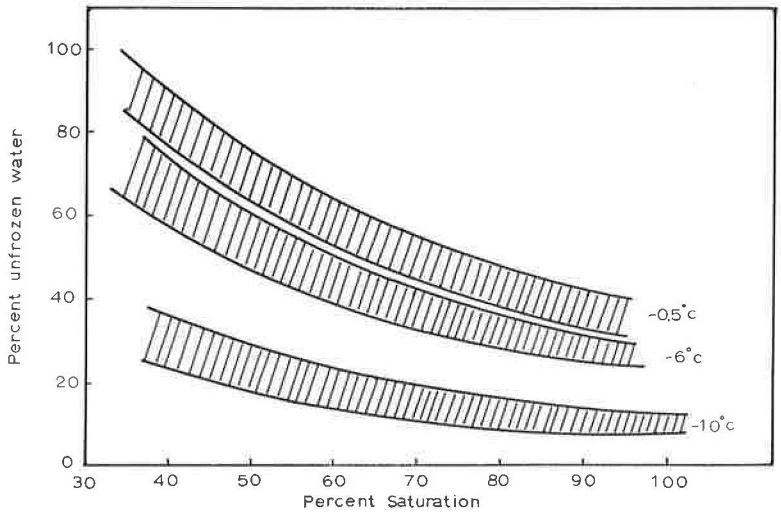

Figure 7. Percent saturation and percent unfrozen water.

Bearing in mind that the samples tested were not completely saturated, the average free energy difference then represents not only menisci or capillarity effects but also the interaction of the adsorbed water layers (as a result of long-range and short-range interaction). In essence, this average free energy difference is the total soil-water stress. It is possible to establish relationships between unfrozen water content or percent of unfrozen water with initial water contents or degree of saturation. Holding atmospheric pressure constant, with increasing initial water contents it follows that the percent unfrozen water will decrease because the average free energy difference of the soil water decreases with increasing water contents. Hence unfrozen water content must also increase with increasing initial water contents because these are all referenced to the same quantity of solid particles. The statement of significance therefore is that as moisture potential decreases, i.e., if the average free energy difference of the water in the soil decreases, the unfrozen water content increases and the percent of unfrozen water will correspondingly decrease.

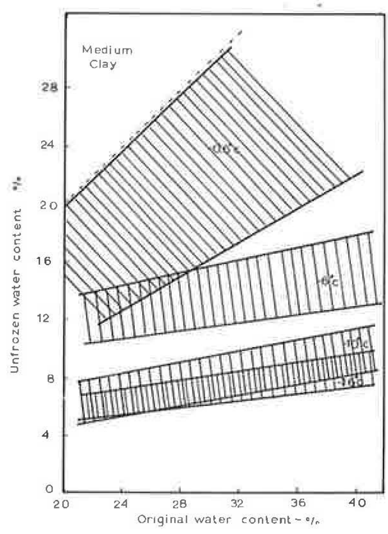

Figure 8. Unfrozen water content and original water content.

Figures 10 and 11 are an attempt to incorporate the saturation effect with initial water contents. This is done by multiplying the water content with the corresponding degree of saturation thus producing the saturation-water content parameter. Bell clay has been used with this method of treatment of unfrozen water content results. Here again, the relationships described reflect those previously shown. The scatter of results however is less since some portion of the error with saturation or water content has been accounted for with the use of the saturation-water content parameter.

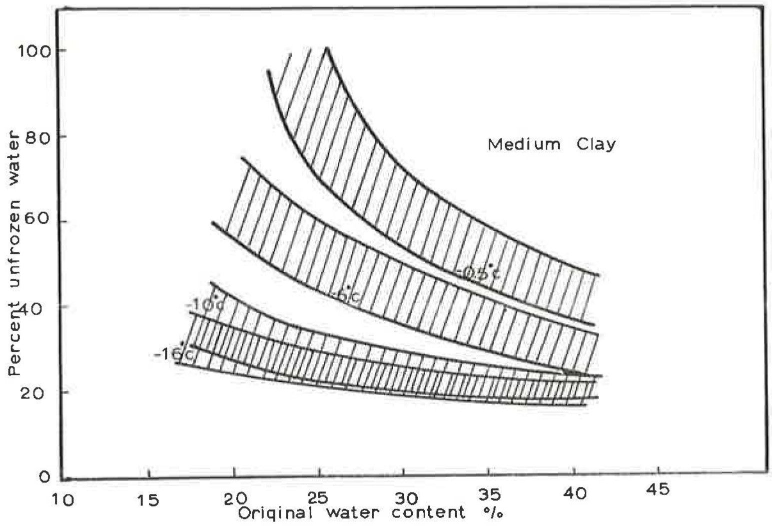

Figure 9. Original water content and percent unfrozen water clay.

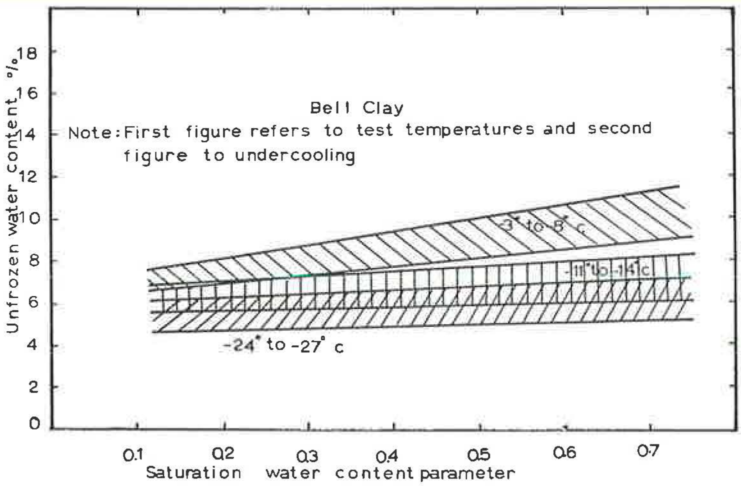

Figure 10. Unfrozen water content and saturation water content parameter.

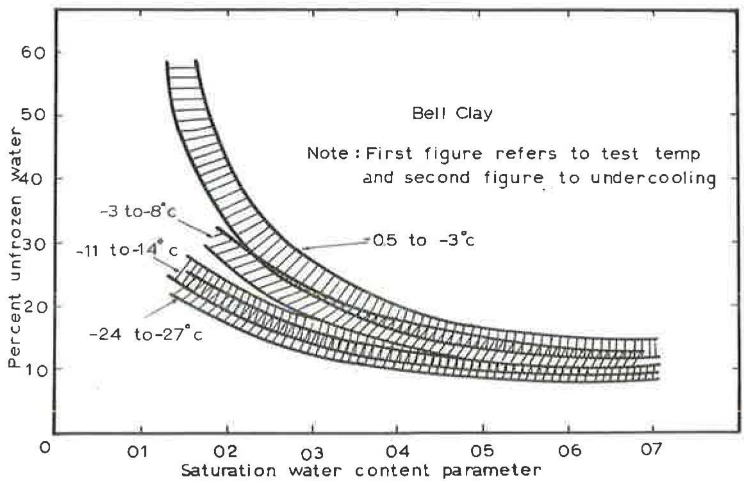

Figure 11. Percent unfrozen water and saturation water content parameter.

Soil Suction and Unfrozen Water

With measurements of both soil suction and quantity of water remaining unfrozen for a particular set of constraints, it is then possible to proceed to establish the interrelationships between soil suction, temperature, soil type and unfrozen water. These relationships may be presented in a variety of ways and Figures 12 through 15 demonstrate some of the more useful ways for gaining a better understanding of soil suction and unfrozen water.

For the medium clay and silt samples, the influence of temperature on unfrozen water content for a series of initial water content conditions is shown in Figure 12. If desired, soil suction or moisture potential may also be included with the water content values. These may be determined from Figures 4 and 5. These relationships seem to be contrary to the demonstrated results of other investigators (10) where unfrozen water content for a fully saturated soil is, under a given set of constraints, dependent only on the freezing temperature. The explanation may be found in the fact that the samples considered in this study were not completely saturated. Hence, considered in terms of total soil moisture stress, it will be obvious that for partially saturated soils, initial water contents would also influence unfrozen water content. Because of differences of configuration for partially saturated soils formed under laboratory

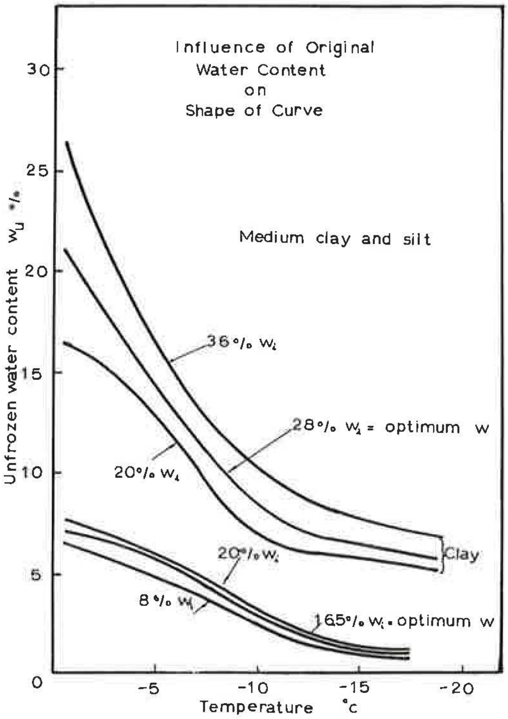

Figure 12. Temperature and unfrozen water content.

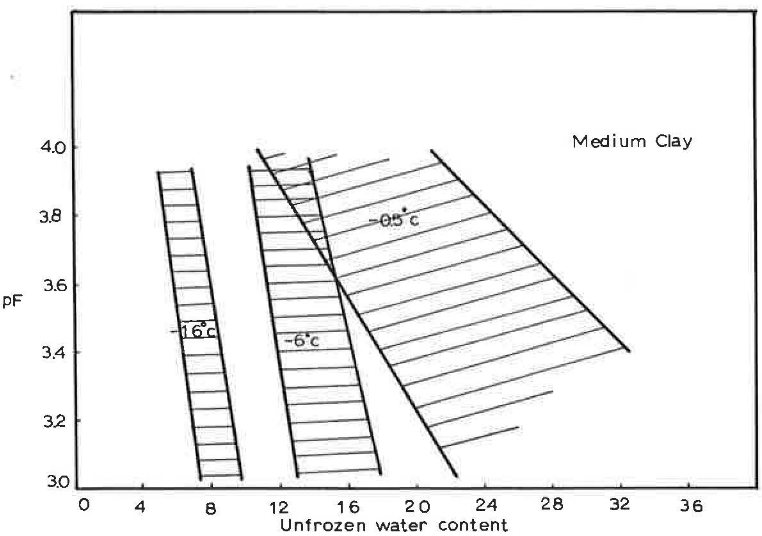

Figure 13. pF and unfrozen water.

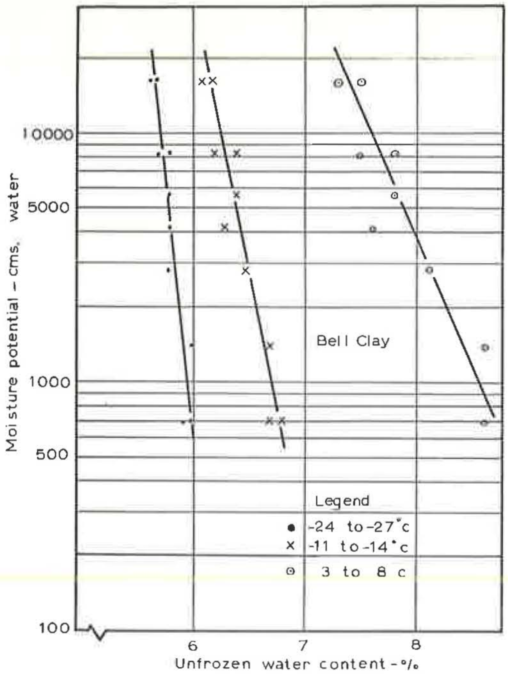

Figure 14. Moisture potential and unfrozen water content.

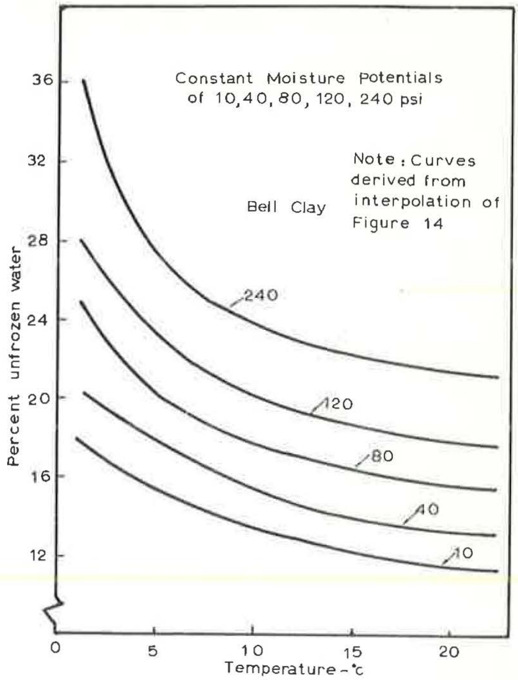

Figure 15. Percent unfrozen water and temperature.

conditions, there would correspondingly be different free energy relationships; this is evident from an examination of the desorption curves for (a) a slurry and (b) a dry-packed sample of the same soil.

The effect of freezing or thawing to the test temperature is shown in Figure 13 where soil suction is directly related to unfrozen water content for the medium clay samples where the right boundary of the bands represent freezing to and the left boundary signifies thawing to the test temperature. Once again, as in all the graphs using bands to portray the relationships shown, the scatter of results is evident. However, the patterns are well defined and the points are well bounded between the limits as stated previously. Figure 14 relates soil suction expressed as moisture potential to unfrozen water content for the Bell clay. Remembering that a decrease in free energy difference of the soil water produces upon freezing of the soil mass corresponding decreases in percent of unfrozen water, and further taking cognizance of the fact that re-arrangement of the arithmetic values will yield unfrozen water contents that will correspondingly increase, the interrelationships mentioned previously can be established. It is important to note that freeze-thaw history does influence the final determination of unfrozen water content. This may possibly be due to the reorientation of particles and other associated mechanisms. In this study, for the thawing portion, the soil samples were generally frozen to a temperature of about 3 C lower than the prescribed test temperature (or as shown in Figs. 10 and 11).

It is important to bear in mind that the relationships described heretofore pertain to measurements of moisture potential or soil suction at room temperature and that these have been used to correlate measured unfrozen water contents. The intention here is to be able to use measured soil suction values at room temperature to predict the quantity of unfrozen water for the soils tested. This would eliminate the necessity for measuring soil suction as a function of temperature—which is inmeasurably more difficult.

Choosing Bell clay as an example, the influence of temperature on the percent of unfrozen water for any one moisture potential or soil suction value may be seen in Figure 15. The moisture potentials were measured at room temperature and do not represent the moisture potential at the same subfreezing temperature. Preliminary tensiometer measurements (between 0 C and -3 C) for silt samples show that soil suction tends to increase as the temperature is lowered below 0 C. However, it is difficult to quantify this phenomenon exactly since one must necessarily consider the fact that there will exist a temperature gradient within the pressure measurement section of the tensiometer. Williams (6) has presented data, using the unique relationship of water content-dry density from oedometer tests, showing that soil suction increases as the temperature decreases from 0 C to -1 C. As verification of this, he has computed soil suction and temperature using the equation proposed by Schofield (2). However, if one bears in mind that this particular equation specifically relates soil suction to temperature depression, it becomes obvious that higher soil suction values must be reflected by greater temperature depressions in the soil water.

In order to relate effects of lowered temperatures on measured soil suction (quite apart from all the previous discussion on soil suction measurements at room temperature) it is necessary to consider contribution to soil suction from two major sources: (a) surface tension forces, and (b) Gouy forces. In the absence of ice formation, lowered temperatures would tend to increase the former and decrease the latter (11). Hence, it becomes necessary to think in terms of the algebraic addition of two quantities, i. e., one increasing and the other decreasing for the sum total demonstration of soil suction. It is possible to have systems where one would completely dominate the other. For silts, surface tension forces would dominate and for active clays, the reverse would be true. Since soil suction measurements performed at room temperature represent the total contribution of these forces for that particular temperature and since it is possible to evaluate the influence of temperature on the demonstration of these forces, it seems reasonable to expect that relationships between soil suction (measured at room temperature) and unfrozen water content can be established.

Acknowledging the relationship between moisture potential and temperature (and the preliminary tensiometer data for silts indicate that as -3 C is reached this relationship seems to become near constant), it is evident that it is possible to utilize initial moisture potential relationships in the study of unfrozen water. It can be noted (Fig. 15) that with increasing initial moisture potentials (i. e., measured at room temperature), the percent of unfrozen water content for any one temperature correspondingly increases. Since the moisture potential is a measure of the average free energy difference of the water in the soil mass, the relationship described may be used interchangeably in terms of room temperature measurements of moisture potential, soil suction or free energy difference of the soil water.

SUMMARY AND CONCLUSIONS

In this paper the terms soil suction (pF) and moisture potential have been used interchangeably. This was done by design because both represent the same measure of the free energy difference of the water in a soil mass. Based on previous studies, it becomes evident from a study of soil-moisture relationships that there could be similar relationships which would establish the phenomenon of partial soil freezing. It then follows that the dependence of unfrozen water in a frozen soil mass on the forces holding water to soil may be directly thought of in terms on a minimal number of parameters. This would bypass the necessity of obtaining an exact definition of the forces that hold water to soils, but would in essence establish a measure of the consequent action of these forces interacting in the soil-water system. The total potential of soil moisture is a useful tool. Although it does not require specific definition of the forces by which water is retained in soils, it permits one to measure the end effect in terms of a convenient parameter. The pressure membrane technique used in this study is relatively accurate if little or no particle reorientation occurs.

The results of this study indicate that the forces holding water to soil measured in terms of the soil suction capacity (pF), or as moisture potential at room temperature, may be used to relate unfrozen water content in partial soil freezing. In terms of moisture potential measured at room temperature, the results show that soil-water systems (and there is no specific requirement for complete saturation of specimens) with higher moisture potentials will upon freezing retain more unfrozen water—when compared to those with lower moisture potentials.

It is necessary to consider moisture potential in terms of specific contributions from surface tension forces and Gouy forces since temperature effects on these are not similar. Since it is possible to qualitatively evaluate the temperature effect on the demonstration of these forces, it then is further possible to summate these effects and use room temperature measurements of moisture potentials to predict unfrozen water contents for soils specifically studied.

ACKNOWLEDGMENTS

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