AN INVESTIGATION OF THE EFFECTS OF FREEZING ON PORTLAND CEMENT CONCRETE

BY

Edward H. Fuller

A Thesis Submitted to the Graduate Committee

For the Degree of

MASTER OF SCIENCE

in

Civil Engineering

APPROVED:

____
Head of Department

____
Dean of Engineering

____
Chairman, Graduate Committee

Virginia Polytechnic Institute
Blacksburg, Virginia
June, 1939

ACKNOWLEDGMENTS

The author desires to express his appreciation to Professor R. B. H. Begg, Head of the Department of Civil Engineering, Virginia Polytechnic Institute, and Associate Professor W. T. Hartmen, Jr., in charge of the Concrete Laboratory, for their invaluable suggestions, and cooperation which enabled the investigation to go forward.

Acknowledgment of assistance is also due to:

Dean E. B. Norris, Dean of Engineering, who with Professor Begg made this research possible by supplying the necessary materials and equipment.

, Manager of the Virginia Polytechnic Institute Creamery, for the use of his equipment.

, Manager of the New River Lumber Company, for the use of his truck.

and , student labaratory assistant for their indispensable aid in the labaratory.

TABLE OF CONTENTS

I. INTRODUCTION

Ever since concrete has risen to prominence as a mterial for the engineer and construction man, it has been desirable to place concrete in winter weather and to give the concrete necessary protection to allow it to gain strength. It is economically desirable to minimize this protection as far as the time element is concerned. The use of salamanders and heating equipment are examples of the economic output necessary.

Much research has been done on the effect of cycles of freezing and thawing. It has long been known that repeated cycles cause a break-down in fresh concrete. Protection is used to guard against this. Consequently, this problem was devised to find at what period the protection is most essential.

The statement of many construction superintendents and veteran concrete workers to the effect that the second night is the danger line caused no little interest in the problem. They intend to convey the idea that if concrete passes the second night without freezing, it will be little harmed by freezing thereafter, and will gain the required strength.

Two instances occuring on the V. P. I. campus also called attention to the elusiveness of the problem. A sidewalk laid during a winter was apparently frozen at laying. However, instead of the break-up expected, the walk is at present one of the most satisfactory on the campus. More recently, during the past winter, a floor slab was apparently frozen when a sudden freeze came at night. After allowing curing ,the floor was loaded to its maximum and deflections were observed by means of a level. Instead of the abnormal result expected, the deflections were well within the design and safe considerations.

To increase conditions to nearer practical, the time of freezing was reduced to one day, which is probably the time concrete would remain forzen as the result of a sudden freeze. After such a period precautions would undoubtedly be taken to thaw the concrete and prevent futher freezing.

Although the heat produced by mass concrete would probably lengthen the time before freezing takes effect, cylinders should give an indication of the expected results, and will approximate results expected in beams and slabs.

II. REVIEW OF LITERATURE

One cycle of freezing and thawing has occupied the attention of very few research workers. Though many opinions coincide, there is also a wide divergence on some points.

Most of the literature deals with long periods of curing at temperatures below normal. However, these give good indications of what one may expect from freezing.

A discovery of interest was to the effect that the quality of the mortar paste rather than soundness of the coarse aggregate used determined to what extend freezing would affect the concrete.[1/] This of course means that the water-cement ratio is the determining factor. The question of aggregate condition with relation to freezing is slightly controversial.

All research points to the danger of placing concrete with a temperature of under 70° F. when there is any danger of freezing. This[2/] temperature of initial curing is primarily the basis for any strength developed in concrete at freezing temperatures after a period of initial curing. The many investigations have shown that concrete gains in strength even while exposed to freezing temperature. However, a decrease in temperature decreases the rate of gain. [3/] This was true at 16° F and 25.5° F. A mean of 27.1° F. exposure showed a retarded gain in strength and a softening and crumbling of the concrete. This was due to the fact that the slight variations from 27.1° F gave cycles of freezing and thawing.

After exposure to sub-freezing temperature a great benefit from warming the concrete has been noted. Some investigators, however, have found that under certain conditions strength of concrete is much higher while forzen.4/ Still others have found that a thawing of such concrete reduces the strength.5/

Work with time elapsing between mixing and freezing has received limited attention. In the Russia Ukraine it was found that concrete frozen before setting would be normal upon thawing6/ while concrete frozen during setting period suffered permanent bad effects. This work was planned to take advantage of the freezing. Most often, of course, it is desired to keep concrete from any freezing for it will usually strike after partial hardening. One day curing at 70° F has been put forward as insufficient, and the safe period of curing in freezing weather has been suggested as being from three and four days7/ to seven to ten days.8/ The latter theory was advanced by Professor C. C. Wiley who noted that the injurious effect of freezing was due to freezing of the cement paste and its drawing away from the coarse aggregate. Thus seven to ten days is advanced as the time required from complete adhesion. The richer the mix the less effect freezing was found to have in all cases.

Mr. A. C. Ringelstein, Graduate Fellow at the Virginia Polytechnic Institute for 1937-1938, in his thesis "An Investigation of the Effects of Abnormal Curing Conditions on Dolomitic Limestone Portland Cement Concrete" observed that although there was a difference in per cent of check cylinder strength for cylinders frozen for various periods of time, the difference in results was extremely slight between one and seven days frozen and also between one and ten days. Hence, it appears that using freezing periods of one and two days should give representative results.

III. INVESTIGATION

A. Object of Investigation.

The object of this investigation was to find the critical stage for the freezing of concrete. That is, it was desired to find the length of time after mixing at which freezing of the concrete would cause a permanent undiminishing loss of strength. Other than that, it was a study of the effects of extremely low temperatures on concrete made with Dolomitic Sand and Portland Cement.

B. Procedure.

1. Plan of Attack

In the effect of freezing on the strength of the concrete, only one of the many variables was considered. This variable was the time elapsed between mixing and pouring and freezing. The time was varied from hours to days.

Although early cylinders were refrigerated for two days, later cylinders were only subjected to one day freezing which proved complete.

The temperature of freezing was that which prevailed in the ice cream cold storage room at the Dairy Husbandry Building. 0° F $\pm$ 10° was the prevailing temperature indicated in observations made at various times. Tests were made at 7 and 28 days with some 90 day tests on early cylinders.

2. Materials and Apparatus

Early cylinders made in 2" x 4" gang molds were made with Petersburg sand, Portland Cement, and water. From past experiments, and by the simple expedient of filling the molds with sand alone, the quantities needed were determined.

A 1:3 mortar by wt. was used, and an optimum amount of water based on workability was added.

The larger cylinders used for the latter part of the thesis were molded in cardboard paraffin treated cylinders 6"x12". The use of this type of cylinder was necessitated by the number of cylinders per run, and the ease of handling when frozen at early stages when it was necessary that the cylinders remain in the forms.

Furthering work with Dolomitic Sand, that type of sand was used as the fine aggregate. The origin of the sand was at the Claytor Dam Quarry of the Radford Limestone Company. This sand was from the shipments used on the dormitories under construction on the campus and met specifications set up for that work. Coarse aggregate was crushed limestone obtained for early cylinders from the V. P. I. Storage Lot, and for the last three runs from a well-graded $1\frac{1}{2}$" aggregate furnished by the Virginian Limestone Corporation.

The cement used in the small cylinders was Penn-Dixie, and in the machine-mixed cylinders Lone Star Cement was used. These cements were obtained through the V. P. I. Storage Lot. The water was taken from the V. P. I. water supply.

Materials for the small cylinders were used in the following proportions:

Wt. of sand req'd to fill one mold for 3 = 930 gr.
Assume 1020 Gr. to allow for packing.

Twelve cylinders = 4080 gr.
On basis of 1:3 mortar by wt.

Wt. of cement = 1360 gr.

Volume of water = 660 c.c.

Materials for the 6"x12" cylinders, which were made in batches of 10, with 20 to a run, were mixed in a 1:2:3 ratio, used in previous research, with $7\frac{1}{4}$ gallons of water per bag of cement.

A list of materials used and their exact proportions is as follows:

1. Weight of cement per cubic foot - 94 lbs 0 oz.
2. Weight of dry rodded dolomitic sand per cubic foot - 110 lbs 8 oz.
3. Weight of dry rodded crushed limestone per cubic foot - 101 lbs 0 oz.

Materials used for one batch of ten cylinders:

Water......... 3.625 gallons

Cement.......0.5 cubic foot........ 47 lbs. 0 oz.

Dolomitic sand.1 cubic foot........110 lbs. 8 oz.

Crushed limestone 1.5 cubic feet...151 lbs. 8 oz.

For the purpose of testing the specimens the 100,000 lb. Rieble machine, the 100,000 lb. Tinius Olsen machine, and the 400,000 lb. Rieble hydraulic motor-driven machine were used. The first two machines were used for 7 day tests on the 6"x12" cylinders, and the Olsen machine was used for all tests on the 2"x4" cylinders, and the latter for 28 day tests on the 6x12" cylinders. As previously stated, the freezing was done in the ice cream storage room on the campus. The weighing was done on the two Fairbanks scales; for the small cylinders the balances weighing to 10 grams were used, and for the large cylinders the scales weighing to one-quarter ounce were used.

3. Preparation of Specimens

There were two different procedures of preparation for the two types of cylinders, large and small. In every case preparation followed only after careful determination of the necessary quantities.

For the small, 2"x4", cylinders an open copper pan was used to hold the mixture. The fine aggregate was weighed in the Fairbanks pan balance and placed in a pile in the pan. After the cement was weighed it was placed over the pile of fine aggregate. By use of the trowel, cement and aggregate were mixed dry, maintaining the pile, until a uniform color indicating thorough mixing was obtained. The materials were always turned over toward the center.

After a good dry mix was obtained, the pile was flattened out, and a spiral ditch in the mixture was made with the trowel spiralling from the center out. Into this spiral, water in the correct amount was poured from a graduate cylinder. Using the trowel the wetted mixture was turned over four times toward the center. Then, a five-minute mixing by hand followed. The method used was that used in making briquettes, that is, interlocked thumbs with the ball of the hand used to knead the mixture.

Filling of the four three-gang molds was accomplished by use of the trowel to scoop concrete from the pan and tamping in 4 one-inch layers, 30 tramps per layer, by means of a steal tamper once specified by A. S. T. M. (American Society for Testing Materials). The cylinders were smoothed on top after the last layer was tamped. Immediately the molds were placed in the moist closet. After 24 hours in the molds, the cylinders were removed from the molds,marked, and returned to the moist closet for such periods as the type of curing permitted. Those to be frozen were removed from the moist closet and placed in the refrigerator according to schedule. Markings indicated batch and cylinder, as E_2 4 the fourth cylinder in the second batch.

Before testing, a plaster cap was mixed and placed on the cylinders to insure even distribution of the load.

In making the 6"x12" cylinders the coarse aggregate was first weighed on the Fairbanks platform scales and placed in the aggregate trough in front of the concrete mixer operated on direct current. Next, the fine aggregate was weighed out and placed in the trough. The cement was weighed and placed alongside the trough and mixer. Finally, the water was measured by means of a two quart cup and placed in buckets near the mixer.

The mixer was started and the aggregated introduced. As soon as aggregates were in the mixer cement was added and the mix was run dry briefly. Measured water was added, and the mixer run for three minutes.

At the end of three minutes the mix was dumped from the mixer into a pan provided for the purpose. From the pan a sample was taken and placed in a slump cone according to A. S. T. M. specifications and the slump was measured giving an indication of the type of mix. Following this the concrete was placed in ten paraffin-coated, cardboard cylinders rodding in three layers with 28 strokes per layer by A. S. T. M. specifications. The top was struck off smooth after the last layer was rodded.

This procedure was again repeated to obtain ten more cylinders to make the necessary twenty cylinders per run.

After 24 hours the forms were stripped and the numbers painted on and the cylinders placed in the curing trough or air, unless the cylinder was to be frozen within 24 hours. In the latter case the forms were left on for 24 hours after removal from the refrigerator at which time cylinders were placed in air or curing trough according to schedule. All other frozen cylinders were placed in air or curing trough immediately after removal from the refrigerator. Numbers such as E_7 3 indicate the third cylinder in the seventh batch.

Curing and tests were carried forward on the schedules indicated. Before testing all cylinders were capped with plaster to assure uniform distribution of the loads as applied by the testing machines.

C. Results.

1. Groups E

The cylinders in groups E were 2" in diameter by 4" high. Six of the cylinders were frozen and six were retained as check cylinders, which means they were cured in ideal conditions. The strength of these latter cylinders were averaged and divided into the strength of individual cylinders to give the per cent of check strengths.

Table E_1

Cyl. No.	Days Frozen	Temp. in (Fahr.)	Temp. out (Fahr.)	Days in M. C.	Age of test (days)	Lead Pounds	Stress lbs.per sq. in.	Per Cent of check strength
7	2	1	1	5	7	8800	2800	92.4
8	2	1	1	5	7	9100	2900	95.7
9	2	1	1	26	28	12600	4010	103.3
10	2	1	1	26	28	12000	3820	98.5
11	2	1	1	88	90	13915	4440	128.0
12	2	1	1	88	90	13800	4400	127.0
Check:								
1	-	-	-	7	7	9700	3035	---
2	-	-	-	7	7	9500	3025	---
3	-	-	-	28	28	12200	3880	---
4	-	-	-	28	28	12200	3880	---
5	-	-	-	90	90	10435	3330	---
6	-	-	-	90	90	11310	3605	---

Remarks: Temperatures read on entering refrigerator. Cylinders 7-12 frozen one day after mixing.

Table E_2

Cyl. No.	Days Frozen	Temp. in (Fahr.)	Temp. out (Fahr.)	Days in M. C.	Age of test (days)	Lead Pounds	Stress lbs.per sq. in.	Per Cent of check strength
7	2	10	9	5	7	8300	2640	89.2
8	2	10	9	5	7	8200	2610	88.6
9	2	10	9	26	28	11300	3600	100.5
10	2	10	9	26	28	11800	3760	105.1
11	2	10	9	88	90	13000	4150	114.2
12	2	10	9	88	90	13000	4150	114.2
Check:								
1	-	-	-	7	7	8800	2800	---
2	-	-	-	7	7	9700	3085	---
3	-	-	-	28	28	10800	3440	---
4	-	-	-	28	28	11700	3720	---
5	-	-	-	90	90	11500	3660	---
6	-	-	-	90	90	11500	3600	---

Remarks: Temperature read on entering refrigerator. Cylinders 7-12 frozen one day after mixing.

Table E_3

Cyl. No.	Days Frozen	Temp. in (Fahr.)	Temp. out (Fahr.)	Days in M. C.	Age of test (days)	Load Pounds	Stress lbs.per sq. in.	Per Cent of check strength
7	2	-2	-1	5	7	8300	2640	89.2
8	2	-2	-1	5	7	8400	2675	90.3
9	2	-2	-1	26	28	12200	3880	100.2
10	2	-2	-1	26	28	13100	4170	107.8
11	2	-2	-1	88	90	14000	4460	110.0
12	2	-2	-1	88	90	13000	4150	102.1
Check:								
1	-	-	-	7	7	9100	2900	---
2	-	-	-	7	7	9500	3020	---
3	-	-	-	28	28	11800	3760	---
4	-	-	-	28	28	12500	3980	---
5	-	-	-	90	90	12500	3980	---
6	-	-	-	90	90	13000	4150	---

Remarks: Temperature read on entering refrigerator-Cylinders 7-12 frozen one day after mixing.

Table E_4

Cyl. No.	Days Frozen	Temp. in (Fahr.)	Temp. out (Fahr.)	Days in M. C.	Age of test (days)	Load Pounds	Stress lbs.per sq. in.	Per Cent of check strength
7	2	9	10	5	7	8800	2800	95.6
8	2	9	10	5	7	8700	2770	94.5
9	2	9	10	26	28	12000	3820	95.5
10	2	9	10	26	28	12100	3850	96.2
11	2	9	10	88	90	11085	3530	97.8
12	2	9	10	88	90	11100	3540	98.0
Check:								
1	-	-	-	7	7	9000	2865	---
2	-	-	-	7	7	9400	2995	---
3	-	-	-	28	28	12100	3860	---
4	-	-	-	28	28	13000	4140	---
5	-	-	-	90	90	11000	3500	---
6	-	-	-	90	90	11680	3720	---

Remarks: Temperature read on entering refrigerator. Cylinders 7-12 frozen two days after mixing.

Table E_5

Cyl. No.	Days Frozen	Temp. in (Fahr.)	Temp. out (Fahr.)	Days in M. C.	Age of test (days)	Load Pounds	Stress lbs.per sq. in.	Per Cent of check strength
7	2	0	0	5	7	8100	2580	88.6
8	2	0	0	5	7	8400	2670	94.8
9	2	0	0	26	28	12200	3880	111.8
10	2	0	0	26	28	11100	3535	101.9
11	2	0	0	88	90	11460	3650	103.1
12	2	0	0	88	90	9405	3000	84.7
Check:								
1	-	-	-	7	7	9200	2930	---
2	-	-	-	7	7	8500	2700	---
3	-	-	-	28	28			---
4	-	-	-	28	28	10900	3470	---
5	-	-	-	90	90	10835	3460	---
6	-	-	-	90	90	11370	3620	---

Remarks: Temperature read on entering refrigerator. Cylinders 7-12 frozen two days after mixing.

Table E_6

Cyl. No.	Days Frozen	Temp. in (Fahr.)	Temp. out (Fahr.)	Days in M. C.	Age of test (days)	Load Pounds	Stress lbs.per sq. in.	Per Cent of check strength
7	2	-1	2	5	7	14500	4610	90.4
8	2	-1	2	5	7	15400	4900	96.1
9	2	-1	2	26	28	16200	5150	85.6
10	2	-1	2	26	28	19000	6050	100.4
11	2	-1	2	88	90	17500	5580	82.6
12	2	-1	2	88	90	19700	6270	92.9
Check:								
1	-	-	-	7	7	15300	4870	---
2	-	-	-	7	7	16700	5320	---
3	-	-	-	28	28	18100	5760	---
4	-	-	-	28	28	19700	6270	---
5	-	-	-	90	90	19700	6270	---
6	-	-	-	90	90	22700	7240	---

Remarks: New cement used. Temperatures read on entering refrigerator. Cylinders 7-12 frozen three days after mixing.

Table E_7

Cyl. No.	Days Frozen	Temp. in (Fahr.)	Temp. out (Fahr)	Days in M. C.	Age of test (days)	Load Pounds	Stress lbs. per sq. in.	Per Cent of check strength
7	2	10	8	5	7	17,100	5450	92.8
8	2	10	8	5	7	17,100	5450	92.8
9	2	10	8	26	28	19,300	6150	102.8
10	2	10	8	26	28	24,000	7640	127.8
11	2	10	8	88	90	22,400	7140	98.1
12	2	10	8	88	90	21,500	6850	94.2
Check:								
1	-	-	-	7	7	17,200	5470	---
2	-	-	-	7	7	19,700	6270	---
3	-	-	-	28	28	18,000	5730	---
4	-	-	-	28	28	19,600	6240	---
5	-	-	-	90	90	21,900	6990	---
6	-	-	-	90	90	23,700	7550	---

Remarks: Temperatures read on entering refrigerator. Cylinders 7-12 frozen two days after mixing.

Summary Table

Group	Per Cent of Check Strength		
	Age		
	7 days	28 days	90 days
E_1	94.0	100.9	127.5
E_2	88.9	102.8	114.2
E_3	89.8	104.0	106.0
E_4	95.0	95.8	97.9
E_5	91.7	106.8	93.9
E_6	93.2	93.0	87.8
E_7	92.8	115.3	96.2

Discussion of Groups E

Results of the tests on the 2"x4" cylinders made without coarse aggregate offer many interesting bases for discussion. All of these cylinders were frozen for 2 days and for the remainder of the time up to the test date were cured in the moist closet.

Groups E_1 E_2 and E_3 were frozen 1 day after mixing. Freezing had the maximum effect at the 7 day test period in the cylinders of these groups. The average per cent of check strength at 7 days was 90.9%. At 28 days the phenomenon of increased strength in frozen cylinders was illustrated when the cylinders tested at an average of 102.6% of check strength. Only one of the cylinders tested in the group showed a strength less than that of the check cylinders, and this one showed 98.5% of check strength which means freezing had little effect. Ninety-day strengths showed the maximum increase of frozen over check cylinders in this group, an increase even greater than that at 28 days. No frozen cylinder had a strength under that of the check cylinders, and the average for the frozen cylinders in the groups was 115.9% of the strength of the check cylinders.

The groups frozen 2 days after mixing, E_4 E_5 and E_7 showed the least effect of the results of freezing at the 7 day tests of any of seven groups. Average for the six cylinders frozen and tested at 7 days in the three groups was 93.2% of the check strength. However, two cylinders in these groups indicated practically the same per cent of check strength as two cylinders in the first groups. At 28 days the average strength of the frozen cylinders was 106.0% of the strength of the check cylinders.

This was the maximum percentage of check cylinder strength at 28 days. The maximum for individual cylinders at 28 days was also in this group at 127.8%, while the minimum was 95.5% which indicates an appreciable effect of freezing. An average of 96.0% of check cylinder strength for the frozen cylinders was obtained on the 90 day test. This illustrated freezing had some effect in the expected direction on the cylinders, although a recovery by 90 days might have been expected. One frozen cylinder showed a gain of strength by a percentage of 103.1 of check cylinder strength while another showed a great loss with 84.7% of check cylinder strength.

The cylinders in group E_6 which were frozen three days after mixing showed a consistent, and increasing loss of strength. At the seven day tests the frozen cylinders showed a strength 93.2% of that of the check cylinders. There was little change at 28 days with those frozen showing 93.0% of the strength of the check cylinders. However, a wide deviation in the two cylinders' strength was shown by 85.6% of the check strength for one, and 100.4% for the others. At 90 days the maximum effect for this age was shown by the frozen cylinders which showed a strength 87.8% of that of the check cylinders. There was also a wide deviation from this average with 82.6% for the minimum and 92.9% for the maximum.

Absence of coarse aggregate was probably responsible for minimizing the effect of freezing on all of these cylinders. Many of the irrational results were a result of the inconsistencies in concrete and its strength.

Conclusions - Groups E

From the limited data gathered on Portland Cement Concrete having been frozen and using Petersburg Sand as the only aggregate, the following indications may be observed.

1. By freezing concrete one day after mixing the maximum effect is suffered in 7 day strength.
2. Where freezing shows an adverse effect at 90 days, such effect is very far from being overcome; in other words over 90 days is apparently required to overcome freezing.
3. A concrete without coarse aggregate is not extremely susceptible to the detrimental effects of freezing.

C. Results.

2. Groups F

The cylinders in this group were 6" in diameter by 12" high. Ten of the cylinders were frozen and ten retained as check cylinders. The latter were cured under water for ideal conditions.

Table F_1

Cyl. No.	Temp. in (Fahr.)	Temp. out (Fahr.)	Types of curing except for freezing	Days Cured	Age at Test	Load Pounds	Stress lbs. per sq. in.	Per Cent of check strength
3	-5	-3	In water	4	7	41,470	1470	86.6
7	-5	-3	In water	4	7	29,030	1030	60.7
11	-4	-1	(In water	1				
			(In air	3	7	52,500	1860	109.6
15	-4	-1	In water	4	7	34,180	1210	71.3
19	-4	-1	In water	4	7	44,190	1565	92.2
2	-5	-3	In water	25	28	77,740	2750	106.9
4	-5	-3	In water	25	28	90,900	3220	136.9
10	-5	-3	In water	25	28	93,890	3320	141.0
14	-4	-1	(In water	1				
			(In air	24	28	54,210	1920	81.5
18	-4	-1	In water	25	28	75,490	2670	103.3
Check								
1	-	-	In water	6	7	53,450	1890	---
5	-	-	In water	6	7	53,160	1880	---
9	-	-	In water	6	7	42,700	1510	---
13	-	-	In water	6	7	45,160	1600	---
17	-	-	In water	6	7	45,600	1615	---
6	-	-	In water	27	28	68,060	2410	---
8	-	-	In water	27	28	58,350	2065	---
12	-	-	In water	27	28	74,360	2640	---
16	-	-	In water	27	28	63,890	2260	---
20	-	-	In water	27	28	68,030	2410	---

Remarks: Cylinders 1-10, slump 8"; cylinders 11-20 slump $8\frac{1}{2}$". Cylinders frozen two days after mixing. Temperatures read on entering refrigerator. Cement paste glazed and granular at frozen breaks.

Table F_2

Cyl. No.	Temp. in (Fahr.)	Temp. out (Fahr.)	Type of curing except for freezing	Days Cured	Age at Test	Load Pounds	Stress lbs.per sq. in.	Per Cent of check strength
1	-3	-5	In water	4	7	32,100	1135	61.5
5	-3	-5	In water	4	7	32,370	1145	62.2
11	-3	-5	In water	4	7	71,750	2540	137.8
15	-3	-5	In water	4	7	56,300	1990	108.0
19	-3	-5	In water	4	7	63,170	2240	121.5
4	-3	-5	In water	25	28	46,120	1635	51.2
8	-3	-5	In water	25	28	61,200	2170	68.0
12	-3	-5	In water	25	28	128,500	4550	142.5
16	-3	-5	In water	25	28	115,500	4090	128.1
20	-3	-5	In water	25	28	143,000	5060	158.5
Check								
3	-	-	In water	6	7	32,880	1165	---
7	-	-	In water	6	7	44,520	1580	---
9	-	-	In water	6	7	50,600	1790	---
13	-	-	In water	6	7	73,980	2620	---
17	-	-	In water	6	7	58,340	2060	---
2	-	-	In water	27	28	49,120	1740	---
6	-	-	In water	27	28	58,590	2080	---
10	-	-	In water	27	28	120,000	4250	---
14	-	-	In water	27	28	100,000	3540	---
18	-	-	In water	27	28	123,000	4360	---

Remarks: Cylinders 1-10, slump $8\frac{1}{2}$"; cylinders 11-20 slump $7\frac{1}{2}$". Cylinders frozen four days after mixing. Temperatures read on entering refrigerator. 1, 3, and 5 crumbled; 4 and 8 salty appearance at break; 12, 16 and 20 powdery at break.

Table F_3

Cyl. No.	Temp. in (Fahr.)	Temp. out (Fahr.)	Type of curing except for freezing	Days Cured	Age at Test	Load Pounds	Stress lbs. per sq. in.	Per Cent of check strength
1	-2	-4	In Water	2				
			In air	2	7	30,830	1090	75.4
5	-2	-4	In water	4	7	33,970	1200	82.9
11	-2	-4	In water	4	7	29,670	1050	72.5
15	-2	-4	In water	4	7	29,480	1045	72.2
19	-2	-4	In water	4	7	39,630	1390	96.1
4	-2	-4	In water	25	28	50,500	1790	76.6
8	-2	-4	In water	25	28	66,500	2355	100.9
12	-2	-4	In water	25	28	55,500	1960	84.0
16	-2	-4	In water	2				
			In air	23	28	61,000	2160	92.5
20	-2	-4	In water	25	28	94,500	3350	143.5
Check								
3	-	-	In water	6	7	34,350	1215	---
7	-	-	In water	6	7	51,370	1820	---
9	-	-	In water	6	7	47,470	1680	---
13	-	-	In water	6	7	30,570	1080	---
17	-	-	In water	6	7	40,570	1440	---
2	-	-	In water	27	28	51,000	1805	---
6	-	-	In water	27	28	72,500	2565	---
10	-	-	In water	27	28	88,000	3120	---
14	-	-	In water	27	28	56,000	1980	---
18	-	-	In water	27	28	62,500	2210	---

Remarks: Cylinders 1-10 slump $7\frac{1}{2}$"; cylinders 11-20 slump 8". Cylinders frozen three days after mixing. Temperatures read on entering refrigerator. 1 and 5 stone separated. 2, 4 and 6 disintergrated. 12, powdery mortar. 15, glassy at break with salty appearance. 16, white and powdery.

Table F_4

Cyl. No.	Temp. in (Fahr.)	Temp. out (Fahr.)	Type of curing except for freezing	Days Cured	Age at Test	Load Pounds	Stress lbs. per sq. in.	Per Cent of check strength
1	-4	-2	In water	4				
			In air	0	7	34,670	1230	68.8
5	-4	-2	In water	4	7	30,330	1075	60.2
11	-4	-2	In water	4	7	54,750	1940	108.6
15	-4	-2	In water	4	7	53,900	1910	106.9
19	-4	-2	In water	4	7	52,820	1870	104.8
4	-4	-2	In water	25	28	56,000	1980	61.9
8	-4	-2	In water	25	28	90,430	3200	100.0
12	-4	-2	In water	25	28	89,740	3180	99.3
16	-4	-2	In water	4				
			In air	21	28	88,800	3145	98.3
20	-4	-2	In water	25	28	98,000	3470	108.4
Check								
3	-	-	In water	6	7	40,330	1425	---
7	-	-	In water	6	7	44,070	1560	---
9	-	-	In water	6	7	47,370	1680	---
13	-	-	In water	6	7	61,400	2175	---
17	-	-	In water	6	7	59,060	2090	---
2	-	-	In water	27	28	74,000	2620	---
6	-	-	In water	27	28	75,620	2715	---
10	-	-	In water	27	28	99,950	3540	---
14	-	-	In water	27	28	113,000	4000	---
18	-	-	In water	27	28	89,500	3170	---

Remarks: Cylinders 1-10 slump $7\frac{1}{2}$"; cylinders 11-20 slump $7\frac{1}{2}$". Cylinders frozen five days after mixing. Temperatures read on entering refrigerator. 4, 5, 6, 12, 15 and 19 salty appearance at break.

Table F_5

Cyl. No.	Temp. in (Fahr.)	Temp. out (Fahr.)	Type of curing except for freezing	Days Cured	Age of Test	Load Pounds	Stress lbs. per sq. in	Per Cent of check strength
1	-4	-5	In air	4	7	29,590	1050	73.7
5	-4	-5	In water	3	7	25,970	920	64.6
11	-4	-5	In water	3	7	45,060	1600	112.2
15	-4	-5	In water	3	7	39,430	1395	97.9
19	-4	-5	In water	3	7	47,380	1680	118.0
4	-4	-5	In water	24	28	57,660	2040	91.4
8	-4	-5	In water	24	28	66,470	2350	105.3
12	-4	-5	In water	24	28	64,020	2270	101.8
16	-4	-5	In air	25	28	70,240	2490	111.8
20	-4	-5	In water	24	28	96,170	3410	152.9
Check								
3	-	-	In water	6	7	33,300	1180	---
7	-	-	In water	6	7	33,370	1180	---
9	-	-	In water	6	7	36,010	1275	---
13	-	-	In water	6	7	44,020	1560	---
17	-	-	In water	6	7	54,450	1925	---
2	-	-	In water	27	28	54,910	1940	---
6	-	-	In water	27	28	54,930	1940	---
10	-	-	In water	27	28	59,660	2115	---
14	-	-	In water	27	28	61,950	2190	---
18	-	-	In water	27	28	83,790	2950	---

Remarks: Cylinders 1-10 slump 8 3/4"; cylinders 11-20 slump 7". Cylinders frozen one day after mixing. Temperatures read on entering refrigerator. 1 fell apart with powdery appearance. 4, 5, 8, 9, 11, 12, 15, 19 and 20 salty appearance, glossy at break. 20, powdery.

Table F_6

Cyl. No.	Temp. in (Fahr.)	Temp. out (Fahr.)	Type of curing except for freezing	Days Cured	Age of Test	Load Pounds	Stress lbs. per sq. in	Per Cent of check strength
1	-4	4	In air	5	7	42,260	1495	87.7
5	-4	4	In water	4	7	34,120	1210	70.9
11	-4	4	In water	4	7	48,490	1715	100.5
15	-4	4	In water	4	7	45,020	1595	93.5
19	-4	4	In water	4	7	67,470	2385	140.0
4	-4	4	In water	25	28	51,500	1825	66.7
8	-4	4	In water	25	28	60,500	2140	78.3
12	-4	4	In water	25	28	71,000	2510	91.9
16	-4	4	In air	26	28	54,500	1930	70.6
20	-4	4	In water	25	28	87,000	3080	112.8
Check								
3	-	-	In water	6	7	37,320	1320	---
7	-	-	In water	6	7	43,640	1545	---
9	-	-	In water	6	7	57,650	2040	---
13	-	-	In water	6	7	51,180	1810	---
17	-	-	In water	6	7	51,100	1810	---
2	-	-	In water	27	28	54,000	1910	---
6	-	-	In water	27	28	68,000	2410	---
10	-	-	In water	27	28	113,000	4000	---
14	-	-	In water	27	28	73,500	2600	---
18	-	-	In water	27	28	78,000	2760	---

Remarks: Cylinders 1-10 slump 7"; cylinders 11-20 slump $7\frac{1}{2}$". Cylinders frozen for one day, one day after mixing. Temperatures read on entering refrigerator. 1 broke apart and powdery. 5, 8, 11 and 16 powdery. 2 and 4 crumbled entirely. 6 and 18 cone break.

Table F_7

Cyl. No.	Temp. in (Fahr.)	Temp. out (Fahr.)	Type of curing except for freezing	Days Cured	Age of Test	Load Pounds	Stress lbs. per sq. in.	Per Cent of check strength
1	4	-3	In air	6	7	30,240	1070	66.6
5	4	-3	In water	5	7	27,080	960	59.8
11	4	-3	In water	5	7	25,080	890	54.8
15	4	-3	In water	5	7	22,780	805	50.2
19	4	-3	In water	5	7	23,140	820	51.1
4	4	-3	In water	26	28	38,000	1345	59.2
8	4	-3	In water	26	28	41,000	1450	63.8
12	4	-3	In water	26	28	44,000	1560	68.6
16	4	-3	In air	27	28	42,000	1485	65.3
20	4	-3	In water	26	28	42,000	1485	65.3
Check								
3	-	-	In water	6	7	48,350	1710	---
7	-	-	In water	6	7	41,130	1455	---
9	-	-	In water	6	7	60,830	2155	---
13	-	-	In water	6	7	40,130	1420	---
17	-	-	In water	6	7	36,190	1280	---
2	-	-	In water	27	28	52,000	1840	---
6	-	-	In water	27	28	62,000	2200	---
10	-	-	In water	27	28	74,000	2620	---
14	-	-	In water	27	28	63,000	2230	---
18	-	-	In water	27	28	70,000	2480	---

Remarks: Cylinders 1-10 slump $7\frac{1}{2}$"; cylinders 11-20 slump 9". Cylinders frozen for one day, one hour after mixing. Temperatures read on entering refrigerator. 1, 5, 11 and 15 mortar pulled away from stone, frost formations in mortar. 15 fell apart on removal from machine. 19, same appearance, started cracking at bump in side caused by expansion. 8, 12, 16 and 20, frost formation.

Table F_8

Cyl. No.	Temp. in (Fahr.)	Temp. out (Fahr.)	Type of curing except for freezing	Days Cured	Age of Test	Load Pounds	Stress lbs. per sq. in	Per Cent of check strength
1	7	2	In air	6	7	49,970	1765	69.1
5	7	2	In water	5	7	48,140	1700	66.6
11	7	2	In water	5	7	40,400	1430	56.0
15	7	2	In water	5	7	37,030	1310	51.3
19	7	2	In water	5	7	37,650	1330	52.1
4	7	2	In water	26	28	71,500	2530	61.8
8	7	2	In water	26	28	86,000	3045	74.4
12	7	2	In water	26	28	62,000	2195	53.6
16	7	2	In air	27	28	51,000	1805	44.1
20	7	2	In water	26	28	62,000	2195	53.6
Check								
3	-	-	In water	6	7	78,670	2785	---
7	-	-	In water	6	7	79,210	2800	---
9	-	-	In water	6	7	68,020	2410	---
13	-	-	In water	6	7	66,560	2360	---
17	-	-	In water	6	7	67,810	2400	---
2	-	-	In water	27	28	116,000	4110	---
6	-	-	In water	27	28	111,000	3930	---
10	-	-	In water	27	28	129,000	4570	---
14	-	-	In water	27	28	114,000	4040	---
18	-	-	In water	27	28	108,500	3840	---

Remarks: Cylinders 1-10 slump 7"; cylinders 11-20 slump 7". Cylinders frozen one day, two hours after mixing. 1 dry and powdery. 5, 11 and 19 frosty outside, crystalline inside. 15, frost formation inside. 4, 8 and 12 stone pulled out. 4 and 12 frost formation in mortar near outside. 16 powdery. 20 fell completely apart with frost formation throughout.

Table F_9

Cyl. No.	Temp. in (Fahr.)	Temp. out (Fahr.)	Type of curing except for freezing	Days Cured	Age of Test	Load Pounds	Stress lbs.per sq. in.	Per Cent of check strength
1	8	3	In air	6	7	43,000	1520	68.1
5	8	3	In water	5	7	39.200	1390	62.3
11	8	3	In water	5	7	44,400	1570	70.4
15	8	3	In water	5	7	41,980	1485	66.5
19	8	3	In water	5	7	45,200	1600	71.7
4	8	3	In water	26	28	83,000	2940	76.4
8	8	3	In water	26	28	85,500	3025	78.6
12	8	3	In water	26	28	70,000	2480	64.5
16	8	3	In air	27	28	52,000	1840	47.8
20	8	3	In water	26	28	83,000	2940	76.4
Check								
3	-	-	In water	6	7	62,970	2220	---
7	-	-	In water	6	7	60,100	2130	---
9	-	-	In water	6	7	64,600	2285	---
13	-	-	In water	6	7	65,570	2320	---
17	-	-	In water	6	7	62,070	2200	---
2	-	-	In water	27	28	109,000	3860	---
6	-	-	In water	27	28	107,000	3790	---
10	-	-	In water	27	28	118,000	4170	---
14	-	-	In water	27	28	101,000	3580	---
18	-	-	In water	27	28	108,000	3820	---

Remarks: Cylinders 1-10, slump 8"; cylinders 11-20, slump $7\frac{1}{2}$". Cylinders frozen for one day, five hours after mixing. Temperatures read on entering refrigerator. 5, crystalline at break. 11 and 15 salty appearance at break. 8, 12, and 20 fell apart, salty appearance. 16 fell apart dry.

Table F_{10}

Cyl. No.	Temp. in (Fahr.)	Temp. out (Fahr.)	Type of curing except for freezing	Days Cured	Age of Test	Load Pounds	Stress lbs. per sq. in.	Per Cent of check strength
1	8	3	In air	6	7	29,960	1060	51.8
5	8	3	In water	5	7	36,430	1290	63.0
11	8	3	In water	5	7	34,080	1210	59.1
15	8	3	In water	5	7	39,010	1380	67.4
19	8	3	In water	5	7	34,300	1215	59.4
4	8	3	In water	26	28	60,000	2120	66.4
8	8	3	In water	26	28	62,000	2200	68.8
12	8	3	In water	26	28	72,000	2530	79.2
16	8	3	In air	27	28	45,000	1590	49.8
20	8	3	In water	26	28	93,000	3295	103.0
Check								
3	-	-	In water	6	7	52,540	1860	---
7	-	-	In water	6	7	52,880	1870	---
9	-	-	In water	6	7	52,700	1865	---
13	-	-	In water	6	7	62,120	2200	---
17	-	-	In water	6	7	68,110	2415	---
2	-	-	In water	27	28	92,000	3260	---
6	-	-	In water	27	28	82,000	2900	---
10	-	-	In water	27	28	104,000	3685	---
14	-	-	In water	27	28	82,000	2900	---
18	-	-	In water	27	28	91,500	3240	---

Remarks: Cylinders 1-10, slump $6\frac{1}{2}$"; cylinders 11-20, slump 7". Cylinders frozen for one day, three hours after mixing. Temperatures read on entering refrigerator. 5 and 11 had slight frost formation at break. 5, 11 and 19 had crystalline appearance at break. 4, 8, 12, 16 and 20 fell apart. 4 powdery. 8 glazed. 12 and 20 salty appearance. 16 slight frost formation.

Summary Table

Group		Per Cent of Check Strength Age: 7 days	Per Cent of Check Strength Age: 28 days
F_1	1	84.1	113.9
	2	77.7	122.0
F_2		98.2	109.7
F_3	1	79.8	99.5
	2	80.9	101.2
F_4	1	89.9	93.6
	2	--	92.4
F_5	1	93.3	112.6
	2	98.2	112.8
F_6	1	98.5	84.1
	2	101.2	87.4
F_7	1	56.5	64.4
	2	54.0	64.2
F_8	1	59.0	57.5
	2	56.5	60.8
F_9	1	67.8	68.8
	2	67.7	74.0
F_{10}	1	60.1	73.5
	2	62.2	79.2

1- Including cylinder cured in air.
2- Excluding cylinder cured in air.

Discussion of Groups F

The large 6"x12" cylinders which made up these groups were expected to illustrate more fully than the cylinders in Groups E, the effects of freezing. A survey of the results indicated that such was the case. These cylinders were frozen for two days for some and one day for the rest.

In Group F_1 the cylinders were frozen for two days, two days after mixing. The frozen cylinders showed quite a loss of strength at seven days. General average strength of the frozen cylinders was 84.1% of the strength of the check cylinders. This average was raised from 77.1% by the cylinder which was cured in air after freezing and exhibited a strength 109.6% of that of the check cylinders. At 28 days, it was again found that the frozen cylinders were stronger than the check cylinders with the exception of the cylinder cured in air after freezing. The averages were 122.0% and 113.9% of the check cylinder strength. Reduction in the latter was due to the cylinder cured in air after freezing which exhibited only 81.5% of the strength of check cylinders. The percentage of check strength at 28 days was highest in this group.

Cylinders in Group F_2 were frozen for two days, four days after mixing. The average strength at 7 days showed the effects of freezing only slightly with 98.2% of the check cylinder strength showing in the frozen cylinders. There was, however, a wide deviation from that average in the individual cylinders with a minimum of 61.5% and a maximum of 137.8%.

Breaking the results down into each of the two batches the loss is still small but with less deviation. At 28 days the average strength of the frozen cylinders was 109.7% of the average strength of the check cylinders. A wide variation was also noted here. Comparing cylinder for cylinder within each batch, only two frozen cylinders were found to be weaker than the check cylinders. Even this was overcome by averaging within a batch, and the frozen cylinders showed a per cent above 100, which indicates greater strength than check cylinders.

Group F_3 contained cylinders which were frozen for two days three days after mixing. At 7 days the average strength of the frozen cylinders showed a loss of about 20% from the average strength of the check cylinders. Including the cylinder cured in air after freezing reduced the average slightly, yet that cylinder with 75.4% of check strength was not the cylinder with minimum strength. There were two weaker. The variation from the averages of 79.8% and 80.9% was not as pronounced as some previous results had shown. At 28 days the average of the frozen cylinders showed hardly any effect from freezing. The general average was 99.5% of the strength of the check cylinders, and the average excluding the cylinder cured in air after freezing was 101.2% of the strength of check cylinders. Cylinder 20 showed a strength 143.5% of that of the average of the check cylinders, and was stronger than any individual check cylinder. All other frozen cylinders showed less strength than individual check cylinders. In cylinders 1 and 5 it was noted that the stone separated from the mortar.

The group of cylinders on which the longest time elapsed between mixing and freezing was F_4. Cylinders in this group were frozen for two days, five days after mixing, and thus were tested immediately after removing from the refrigerator for the 7 day results. At 7 days the frozen cylinders showed appreciable loss in strength. The general average showed 89.9% of the check cylinder strength. As there was no chance for air curing to 7 days, the calculation excluding the air-cured cylinder was omitted. The minimum strength exhibited was 60.2% of check strength and the maximum 108.6%. Again studying cylinders within batches, the deviation was less, and all frozen cylinders exhibited less strength than the check cylinders within the respective batches. A slight gain with relation to check cylinders was exhibited by the frozen cylinders at 28 days. One cylinder at 61.9% of check cylinder strength was far below the average of 93.6% and 92.4% of check cylinder strength for the frozen cylinders. The cylinder cured in air after freezing was the closest to the average, but was above it. There were two frozen cylinders stronger than the check cylinders within their batches.

Group F_5 contained the cylinders which were frozen for two days one day after mixing. At 7 days the freezing seemed to have had little effect for the general average of frozen cylinders' strength was 93.3%, while that excluding the air-cured cylinder was 98.2%. Even with its low strength at 73.7%, the air-cured cylinder was not the weakest, as one other cylinder had only 64.6% of the check cylinder strength. There were wide variations from the average, and the cylinders exhibiting over 100%

of check cylinder strength were stronger in most cases than the check cylinders within their batches. At 28 days the averages of the frozen cylinders showed 112.6% and 112.8% of the check cylinder strength. The increase of .2% on excluding the air-cured cylinder illustrated how close that cylinder was to the average. Only one frozen cylinder exhibited less strength than the check cylinders' general average at 91.4%; and that cylinder was stronger than all but one of the check cylinders from its batch.

Also frozen one day after mixing were the cylinders in group F_6. However, they were only frozen for one day as were all the remainder of the groups. The general average for frozen cylinders at 7 days seemed to illustrate little effect from freezing with a general average of 98.5% of check cylinder strength and an average, excluding the cylinder cured in air, 101.2% of check cylinder strength. A break-down to individual cylinders showed that again the air-cured cylinder was not the weakest. The general average follows closely the relation between frozen and check cylinders within each batch with one exception, a frozen cylinder which reached 140% of the average check cylinder strength, and was far above any individual cylinder. At 28 days, the average strength of the frozen cylinders dropped in relation to the check cylinders to a general average of 84.1%, and an average exclusive of air-cured cylinder of 87.4%. One check cylinder was lower than all but one of the frozen cylinders, and matching cylinders within batches, all but one of the frozen cylinders were lower than the average for the b atch.

In Group F_7 the cylinders which were frozen were subjected to the freezing temperatures for one day, one hour after mixing. At 7 days, the effect of freezing reached its maximum in this group. A general average of the frozen cylinders showed that they only reached 56.5% of the strength of the check cylinders, With the cylinder cured in air after freezing displaying 66.6% of the strength of the check cylinders, its exclusion from the average caused a lowering to 54.0% of the check strength. The results were remarkably uniform. All cylinders frozen and tested at seven days showed frost formation in the mortar, and the mortar apparently pulled away from the stone. One cylinder fell completely apart on its removal from the machine. Maximum effect of freezing was also noted in the group at 28 days. The strength of the frozen cylinders showed a general average of 64.4% of the strength of the check cylinders. Excluding the cylinder cured in air after freezing, the average was reduced to 64.2% of the check strength. As such a small reduction indicated, the air-cured cylinder was very close to the average. There was one cylinder weaker at 59.2% of the check strength. The frozen cylinders at 28 days showed the same frost formation in the mortar as was observed at 7 days, and did not reach the strength of the 7 day check cylinders.

Frozen for one day, two hours after mixing, the cylinders in Group F_8 exhibited only a slightly higher strength in relation to check cylinders than those frozen 1 hour after mixing. The general average on frozen cylinders at 7 days was 59.0% of the strength of check cylinders.

Excluding the cylinder cured in air after freezing reduced the average to 56.5% of the check strength. The cylinder cured in air again exhibited the highest strength of those frozen with 69.1% of the strength of the check cylinders. Only one cylinder exhibited a frost formation on the inside, while the remainder showed frost on the outside and crystalline particles on the inside.

The frozen cylinders in group F_9 which were subjected to freezing for one day, five hours after mixing, showed the highest relative strength of the cylinders frozen within the short periods after mixing covered by this investigation. The general average strength of the frozen cylinders was 67.8% of the strength of the check cylinders; excluding the frozen cylinder cured in air, the average of the frozen cylinders was 67.7% of the check strength. Results were very uniform, and in only one cylinder did the affects of freezing show as they had in the two preceding groups. This cylinder had crystalline particles at the break.

In group F_{10} the cylinders so exposed were frozen for one day, three hours after mixing. The relative strength showed a slight increase at 7 days over those frozen two hours after mixing and tested at 7 days. A general average of frozen cylinders showed 60.1% of the strength of check cylinders. Excluding the cylinder cured in air after freezing, raised the average to 62.2% indicating that the air-cured cylinder was below average. As a matter of fact, that was the weakest cylinder at

51.8% of the average check strength. Two frozen cylinders showed a slight frost formation at break as was previously noted. Four of the frozen cylinders showed a crystalline appearance at the break.

Conclusions - Groups F

Freezing of Portland Cement Concrete using Dolomitic Sand as the fine aggregate gave rise to the following indications:

1. The critical period in the freezing of concrete occurs within the first six hours after its mixing.
2. Freezing one hour after mixing when a partial set has occurred has the maximum effect on the concrete which is apparently permanent.
3. The effect of freezing decreases gradually within the first six hours, at least, and thereafter decreases more rapidly.
4. The ultimate strength of concrete at 28 days is reduced by freezing occurring at any time within five days after mixing.
5. Presence of a coarse aggregate as used in general practice increases the effect of freezing in concrete.

C. Results.

3. Groups M S

These cylinders were 6"x12" cylinders made by Mr. M. N. Salgo, Graduate Fellow, 1937-1938. Due to lack of time they were allowed to age for a year and left for the author to test. The results follow, and as noted, conclusions were based on relative strengths between steam-cured and check cylinders. The latter were ideal cylinders cured in water.

Table M_1 S

Date made: 4-24-38
Date steam treated: 4-26-38
Date tested: 5-17-39

Temperature: 335° F.
Pressure: 123 lbs./sq.in.(gage)
Age: 1 year, 23 days

Cylinder	Curing after steam treatment	Strength Pounds	Per Cent of check strength
M 1 S 1	In water	88,000	85.2
M 1 S 9	In water	82,000	79.3
M 1 S 6	In air	49,000	47.4
M 1 S 8	In air	50,000	48.4
Check:			
M 1 S 3	---	107,000	---
M 1 S 4	---	109,000	---
M 1 S 7	---	96,500	---
M 1 S 10	---	100,000	---

Remarks: Check cylinders cured in water. Time to reach steam pressure in chamber was 15 minutes. The same time was required to release pressure gradually. Pressure was held for five hours.

Slump 7"

All cylinders tested on Riehle Testing Machine (hydraulic)

Table M_2 S

Date Made: 4-27-38
Date steam treated: 4-28-38
Date tested: 5-17-39

Temperature: 325° F.
Pressure: 125 lbs/sq.in. (gage)
Age: 1 year, 20 days

Cylinder	Curing after steam treatment	Strength Pounds	Per Cent of check strength
M 2 S 6	In water	105,000	102.0
M 2 S 7	In water	104,500	101.5
M 2 S 9	In air	48,000	46.6
M 2 S 10	In air	52,500	50.9
Check:			
M 2 S 1	---	106,000	---
M 2 S 2	---	109,000	---
M 2 S 3	---	98,500	---
M 2 S 4	---	98,500	---

Remarks: Check cylinders cured in water. Time to reach steam pressure in chamber was 15 minutes. The same time was required to release pressure gradually. Pressure was held for five hours.

Slump 6 1/4"

All cylinders tested on Riehle Testing Machine (hydraulic).

Table M_3 S

Date made: 4-29-38
Date steam treated: 4-30-38
Date tested: 5-17-39

Temperature: 300° F.
Pressure: 60 lbs./sq.in.(gage)
Age: 1 year, 18 days

Cylinder	Curing after steam treatment	Strength Pounds	Per Cent of check strength
M 3 S 1	In water	101,000	98.4
M 3 S 2	In water	112,000	109.1
M 3 S 7	In air	62,000	60.4
M 3 S 9	In air	55,000	53.6
Check:			
M 3 S 3	---	142,000	---
M 3 S 4	---	146,000	---
M 3 S 6	---	94,500	---
M 3 S 8	---	131,000	---

Remarks: Check cylinders cured in water. Time to reach steam pressure in chamber was 15 minutes. The same time was required to release pressure gradually. Pressure was held for five hours.

Slump 5"

All cylinders tested on Riehle Testing Machine (hydraulic)

Table M_4 S

Date made: 4-30-38
Date steam treated: 5-1-38
Date tested: 5-18-39

Temperature: 300° F.
Pressure: 62 lbs./sq.in. (gage)
Age: 1 year, 18 days

Cylinder	Curing after steam treatment	Strength Pounds	Per Cent of check strength
M 4 S 2	In water	72,500	64.5
M 4 S 3	In water	73,000	65.0
M 4 S 5	In air	44,000	39.2
M 4 S 6	In air	52,000	46.3
Check:			
M 4 S 7	---	141,000	---
M 4 S 8	---	109,000	---
M 4 S 9	---	97,000	---
M 4 S 10	---	102,000	---

Remarks: Check cylinders cured in water. Time to reach steam pressure in chamber was 15 minutes. The same time was required to release the pressure gradually. The pressure was held for five hours.

Slump 6 3/4"

All cylinders were tested on Riehle Testing Machine (hydraulic)

Table M_5 S

Date made: 5-4-38
Date steam treated: 5-5-38
Date tested: 5-18-39
Temperature: 260° F.
Pressure: 26 lbs./sq.in. (gage)
Age: 1 year, 14 days

Cylinder	Curing after steam treatment	Strength Pounds	Per Cent of check strength
M 5 S 5	In water	93,000	82.1
M 5 S 6	In water	115,000	101.3
M 5 S 9	In air	49,500	43.7
M 5 S 10	In air	41,000	36.2
Check			
M 5 S 1	---	136,000	---
M 5 S 2	---	117,000	---
M 5 S 3	---	113,000	---
M 5 S 4	---	86,500	---

Remarks: Check cylinders cured in water. Time to reach steam pressure in chamber was 10 minutes. The same time was required to release pressure gradually. The pressure was held for five hours.

Slump 7 3/4"

All cylinders tested on Riehle Testing Machine (hydraulic)

Table M_6 S

Date made: 5-7-38
Date Steam Treated: 5-8-38
Date tested: 5-18-39
Temperature: 250° F.
Pressure: 23 lbs./sq.in.(gage)
Age: 1 year, 11 days

Cylinder	Curing after steam treatment	Strength Pounds	Per Cent of check strength
M 6 S 6	In water	----	---
M 6 S 8	In water	122,000	97.2
M 6 S 9	In air	40,000	31.9
M 6 S 10	In air	46,000	36.7
Check			
M 6 S 1	---	128,000	---
M 6 S 2	---	132,000	---
M 6 S 3	---	126,000	---
M 6 S 4	---	115,000	---

Remarks: Check cylinders cured in water. Time to reach steam pressure in chamber was 10 minutes. The same time was required to gradually release pressure. The pressure was held for five hours.

Slump 7 1/4"

All cylinders were tested on Riehle Testing Machine (hydraulic)

Table M_7 S

Date made: 5-11-38
Date steam treated: 5-12-38
Date tested: 5-18-39

Temperature: 350° F.
Pressure: 150 lbs./sq.in.(gage)
Age: 1 year, 7 days

Cylinder	Curing after steam treatment	Strength Pounds	Per Cent of check strength
M 7 S 6	In water	31,000	27.2
M 7 S 8	In water	33,000	29.0
M 7 S 9	In air	46,000	40.5
M 7 S 10	In air	40,000	35.2
Check:			
M 7 S 1	---	125,000	---
M 7 S 2	---	133,000	---
M 7 S 3	---	103,000	---
M 7 S 4	---	94,000	---

Remarks: Check cylinders cured in water. Time to reach steam pressure was 20 minutes. The same time was required to release pressure gradually. The pressure was held for five hours.

Slump 6 3/4"

All cylinders were tested on Riehle Testing Machine (hydraulic)

Table M_8 S

Date made: 5-12-38
Date steam treated: 5-13-38
Date tested: 5-18-39

Temperature: 350° F.
Pressure: 150 lbs./sq.in.(gage)
Age: 1 year, 6 days

Cylinder	Curing after steam treatment	Strength Pounds	Per Cent of check strength
M 8 S 6	In water	35,000	29.2
M 8 S 10	In water	32,500	27.2
M 8 S 5	In air	35,500	29.7
M 8 S 9	In air	37,000	30.9
Check:			
M 8 S 1	---	128,000	---
M 8 S 2	---	120,000	---
M 8 S 3	---	116,000	---
M 8 S 4	---	115,000	---

Remarks: Check cylinders cured in water. Time to reach steam pressure was 20 minutes. The same time was required to release pressure gradually. The pressure was held for five hours.

Slump 6 3/4"

All cylinders tested on Riehle Testing Machine (Hydraulic).

Summary Table

Group	Per Cent of Check Strength Type of Curing	
	In Water	In Air
M 1 S	82.2	47.9
M 2 S	101.8	48.8
M 3 S	103.8	57.0
M 4 S	64.8	42.8
M 5 S	91.7	40.0
M 6 S	97.2	34.3
M 7 S	28.1	37.8
M 8 S	28.2	30.3

Discussions of Groups M S

In Group M_1 S, a temperature of 335° F. and a steam pressure of 123 lbs./sq. in. (gage) was apparently harmful to the cylinders so treated. The average strength of steam cured cylinders cured also in water was 82.2% of the strength of the check cylinders. Cylinders cured in air after steam curing exhibited only 47.9% of the check strength.

Cylinders in Group M_2 S which were steam cured, were subjected to a temperature of 325° F. and a pressure of 125 lbs./sq. in. (gage). This seemed to be beneficial if followed by curing in water, for cylinders so cured reached 101.8% of the strength of the check-cylinders. Curing in air for the year after steam curing, seriously retarded the strength to 48.8% of the check strength. This, however, was an increase over the previous set of cylinders. It was noted that all cylinders steam cured had an exceptionally dry appearance at the break.

Steam curing also seemed to benefit the cylinders in Group M_3 S when they were subjected to a temperature of 300° F. and a pressure of 60 lbs./sq.in. (gage). The average for the cylinders water-cured after steam treatment was 103.8% of the strength of the check cylinders. One of the cylinders was slightly below check strength at 98.4%. The cylinders cured in air after steam curing, showed a marked increase over previous cylinders of that type with 57.0% average of the check cylinder strength. This run derived the maximum benefits from the use of steam as a curing medium.

Curing cylinders at 300° F. under 62 lbs./sq.in. (gage) pressure was of no benefit to the cylinders in groups M_4 S . Such curing even reduced strength to an average of 64.8% of the strength of check cylinders for cylinders cured in water after steam curing. Those afterwards cured in air exhibited only 42.8% of the strength of check cylinders. It was again noted that steam-cured cylinders were exceptionally dry at the breaks.

In group M_5 S cylinders were cured at a temperature of 260° F. and a pressure of 26 lbs./sq.in. (gage). One cylinder so cured, and afterward cured in water, showed a strength 101.3% of the strength of check cylinders. However, the other cylinder at 82.1% lowered the average to 91.7% of check strength. Cylinders cured in air after steam curing showed a strength only 40.0% of the check strength.

The loss of one cylinder cured in water after stem, seriously handicaps the value of the tests on group M_6 S. Cylinders in this group were cured at a temperature of 250° F. and a pressure of 23 lbs./sq.in. (gage). The cylinder cured in water after steam showed a strength 97.2% of that of the check cylinders. Curing in air after steam gave a strength only 40.0% of that of check cylinders.

Lowest relative strengths for cylinders cured in water after steam were found in group M_7 S. These cylinders were subjected to a temperature of 350° F. and a pressure of 150 lbs./sq.in. (gage). An average strength of only 28.1% of the strength of check cylinders was exhibited by cylinders cured in steam and water. The average for cylinders cured in air and water was greater at 37.8% of the check strength.

The lowest relative strengths for cylinders cured in air after steam were found when steam-curing was at 350° F. temperature, and a pressure of 150 lbs./sq.in. (gage) as in group M_8 S. Cylinders in this group cured in steam and water showed a strength of 28.2% of the check strength. Although the steam and air strength is minimum in this group, it is greater than the above strength, standing at 30.3% of the strength of check cylinders.

It was noted that in most cases steam-cured cylinders were dry and porous. The cylinders cured entirely in water showed a very compact structure on breaking, and the strengths also showed this.

Conclusions - Groups M S

Steam-curing of Portland Cement Concrete gave rise to the following conclusions:

1. As far as this investigation is concerned, a temperature of 300° F. and a pressure of 60 lbs./sq.in.(gage) is the most beneficial condition for steam curing.

2. The slight increase in strength gained by steam curing is not worth the economic output necessary for steam curing.

3. Extreme care must be exercised in control of steam chamber conditions and after-curing.

IV. SUMMARY

The results of this investigation may serve as the basis for some conclusions with regard to the curing of Portland cement concrete. Some of the more important conclusions are as follows:

1. A concrete, if it may be classed as such, consisting of fine aggregate, cement, and water, is not subject to the extreme effects of freezing as is a true concrete containing a coarse aggregate.
2. Maximum loss of strength, which is evidently long-enduring is suffered by concrete frozen in an extremely green stage when frost enters mortar paste.
3. Freezing may be harmful at any time within the first week. However, in most cases a recovery is indicated.
4. Steam curing, if not carefully controlled at optimum conditions, will result in loss of strength in a concrete.
5. The expansion and drying which occur at the temperatures in the steam chamber apparently are the cause of harmful results in steam curing.

It must be borne in mind that the limitations of data gathered make these conclusions more indicative than conclusive. There is still much room for further research at this institution along the line of both problems presented herein.

Long-time studies are of value in both of these problems. However, the turn-over in graduate students works a hardship in doing understanding work on long-time studies.

Interesting in view of the work done on Dolomitic limestone sand in the local laboratory are the actual strengths obtained in this year's work. Without any attempt to turn out a strong concrete, the water-cement ratio used, along with the type of sand produced nearby, gave an extremely good strength on properly cured cylinders.

V. LITERATURE CITED

1. Jackson, F. H., and Werner, G. - "The Resistance of Concrete to Frost Action" (Abstract); Public Roads, April, 1932.

2. Timms, A. G. and Whitey, N. H. - "Temperature Effects on Compressive Strength of Concrete"; Journal, American Concrete Institute, January-February, 1934; Proceedings, V.30, p. 159.

3. McDaniel, A. B. - "Influence of Temperature on the Strength of Concrete"; Bulletin No. 81, University of Illinois Engineering Experiment Station, July, 1915.

4. Frost, R. V. - "Cooperative Investigation on Strength of Frozen and Unfrozen Concrete" (Abstract); Building Science Abstracts (London), V. 3, p. 259, July 1929.

5. Murphy, R. W. - "Higher Strength Tests of Frozen Concrete"; Engineering News-Record, V. 105, p. 186, July 31, 1930.

6. Gunzburg, A. M. - "Frozen Concrete Used in Russian Building"; Engineering News-Record, V. 107, p. 207, August 6, 1931.

7. Howard, J. E. - "Test of Effect of Low Temperature"; Engineering Record, May, 1905, p. 521.

8. Wiley, C. C. - "Effect of Temperature on Strength of Concrete"; Engineering News-Record, V. 102, p. 179, January 31, 1929.

VI. BIBLIOGRAPHY

1. Batchelder, W. H. - "Significant Tests of Frost Action on Concrete"; Engineering News-Record, V. 101, p. 882, December 13, 1928.

2. Foley, R. A. - "Effect of Temperature on the Curing of Concrete"; Proceedings, American Concrete Institute, V. 25, p. 566, 1929.

3. Johnson, R. C. - "Winter Concreting Methods"; Journal, American Concrete Institute, V. 1, p. 397 and 904, February and June, 1930. (Proceedings, V. 26, 1930)

4. Timms, A. G. and Whitey, N. H. - "Further Studies of Temperature Effects on Compressive Strength of Concrete"; Journal, American Concrete Institute, November-December, 1934; Proceedings, V. 31, p. 165.