COLD WEATHER EFFECTS

ON

FRESH CONCRETE

Thesis presented for the
Degree of Master of Engineering
by Gordon W. Spratt

McGill University

May 1956

CONTENTS

I INTRODUCTION

1.1 Purpose of the Experiment:

The severity of the Canadian winters has, in the past, and does now, affect the construction business. Not only does it lower the efficiency of the working men, it affects the quality of the finished product. This is particularly noticeable in concrete construction where:

1. The formwork is erected more carelessly.
2. Batching weights are less accurate due to human failure and frost affecting the moving parts of the scales.
3. Placing and vibrating are poorly done due to the men being cold.
4. Proper precautions before, during and after placing of concrete are not taken, resulting in the concrete being exposed to cold weather.

It is the latter situation which has led to the greatest number of failures; for hardly a winter goes by without some important structure failing due to frozen or exposed concrete.

Therefore, the purpose of this thesis will be to investigate some of the cold weather effects on fresh concrete not protected from below freezing weather.

1.2 Historical Background:

Until fairly recently it has been a matter of debate amongst builders and engineers as to what extent concrete is damaged by freezing, particularly in its early stages. Conflict of opinion has been fairly severe in some cases. Also, the mechanism by which concrete is damaged by frost has not definitely been established. A review of the literature establishes the following experimental evidence and gives the opinions of those involved with the problem.

In 1915 McDaniels (5) compiled results of tests on 6" x 6" cubes, 6" x 6" cylinders and 8" x 16" cylinders exposed to variable temperatures above and below the freezing point. His conclusions, based on the results of the experiments, were as follows:

1. Under uniform temperature conditions concrete showed an increase of strength with age. For any temperature the rate of increase decreased with age, and the rate of increase was lower at lower temperatures.
2. At seven days concrete maintained at 60° - 70°F showed double the strength of the same concrete kept at 32° - 40°F.
3. Specimens subjected to temperatures above and below the freezing point while green were seriously injured.

Gunzburg (4), of the U.S.S.R., stated that for the period 1905 to 1931 he used in winter concreting a method differing from the accepted, i.e., he purposely allowed the concrete to freeze before its initial set. The cement and aggregates for the mix were cold and the water temperature was between 40° and 50°F. The forms were left in place until spring. When spring came, the concrete, which began to thaw, was wet down with water daily until enough strength was acquired for the forms to be removed. Gunzburg stated that all buildings built in this manner had proved satisfactory.

Muir (7) wrote that a method similar to Gunzburg's (4) was used in Minneapolis in 1910 when a rubble foundation was being laid for the Meyers Arcade. A sand cement mortar was used and the temperature was 20 degrees below zero. The contractor had heard that concrete would set while frozen, and reasoned that the mortar would also. He guaranteed replacement under architectural supervision if any defects were found within a year. A concrete slab was also laid in a similar manner. Examination eight months later showed the mortar and the concrete to be harder than the stone of the foundation. It was still considered a perfect foundation in 1931.

In 1934 Timms and Withey (10) published two papers describing tests carried out to determine temperature effects on the compressive strength of concrete. They moulded 1500 three by six inch cylinders from two cements. Three different slumps were used. After varying periods of preliminary storage at 80°F, the cylinders were exposed to three different temperatures 16, 33 and 50°F for varying lengths of time. After exposure the cylinders were warmed in water and in air. Results showed:

a) That gain of strength is negligible while the concrete is frozen.

b) That high losses of compressive strength do occur if the concrete is cured in air after the freezing period, e.g., a 79 percent loss of 28 day strength is noticed if a specimen is frozen at 16 degrees Fahrenheit for one day after a preliminary storage of 6 hours at 80°F. The specimen was air cured at 70°F after thawing.

c) That recovery may reach 90 percent for specimens air cured at 80°F for 6 hours before freezing, providing the curing after freezing is 100 percent humidity at 72°F.

In 1937 Schofield (9) published the results from tests conducted to show the effects of immediate and delayed freezing on permeability, strength and elasticity of concretes and mortars. He cast 1500 specimens from six cements using various slumps. Conclusions worthy of attention are as follows:

1. <u>Effect of immediate freezing</u>:

a) Concrete attains, on the average, 50 percent of the normal unfrozen concrete of the same age. There is little difference in this respect between a 1-day and a 7-day freezing period.

b) Older concretes have less proportionate loss of strength than those tested at earlier periods.

c) Dry concretes suffer less injury than wet concretes especially at early ages.

d) Porosity appears to be greater for concrete suffering a 7-day freezing period than for a 1-day period.

2. Effect of delayed freezing:

a) Dry concretes (2 inch slump) may be frozen solid without practical injury if cured for 24 to 48 hours in room dry conditions before freezing.

b) Wet concretes (9 inch slump) require a considerably longer time of precuring before freezing in order to remain uninjured.

c) Moist cured specimens require a longer period of precuring before freezing in order to remain uninjured.

In 1940 Allin (1) made tests on (a) cubes wholly or partially frozen and (b) cubes made at various temperatures and subsequently exposed to conditions similar to frosty weather. Strengths were determined after various periods of curing. Results indicated that concrete frozen before setting will harden to a large extent, but will suffer permanent losses up to 50 percent. Concrete placed and exposed between 32° and 50°F hardened normally. Specimens mixed and placed at 45°F and placed in air at 26°F reached the freezing point in 8 hours. They showed an ultimate loss of strength of 30 percent. The tests were confirmed by job observations and the general conclusion was that concrete should be protected completely from freezing during construction.

Members (11) of the American Concrete Institute discussed the topic - If concrete freezes during construction:-

1. What is the procedure to save the work?
2. Does a single freezing damage concrete from the standpoint of durability?

The answer to the first question, given by W. Schnarr, was:- Reverse the process, i.e. thaw the frozen concrete by applying live steam. When it is thawed out, apply standard curing procedures.

Answers to the second question were:-

a) Mr. R. B. Young stated that a single freezing almost always affects the strength and durability of concrete frozen while plastic. Compressive strength is reduced 10 to 50 percent. Also, where concrete has internal freeze lines, disintegration will be present. Referring to Gunzburg (4), Young stated he had tried to produce similar results, i.e. full recovery of concrete frozen immediately, but had no success.

b) H. C. Watts had knowledge of a slab that froze immediately after being poured on the ground at 8°F. Fourteen years later the slab was observed to be in good condition.

c) N. H. Withey of the Portland Cement Association quoted results from his tests (10), which showed a reduction in compressive strengths due to early freezing.

d) In Cincinnati during 1930, E. A. Hagy saw footings frozen while plastic. Comparison of cylinders under standard curing conditions with those made from the frozen concrete after it had thawed, showed no significant gain or loss of strength after 6 months.

Collins (3) formulated the following hypothesis to describe the mechanism of failure of concrete during freezing.

"Cooling begins at the exposed surface and extends slowly inwards. When any layer below the surface reaches a sufficiently low temperature, the water in the largest pores begins to freeze and the latent heat given up by it tends to maintain constant temperature at the point of ice formation. The ice crystals so formed are in contact with unfrozen water in the surrounding smaller pores, and, by drawing water from them, the crystals continue to grow.

"As already stated, the force exerted by the ice will be perpendicular to the cold surface, and, if the concrete is of low strength, a plane of weakness parallel to the cold surface will tend to form at the level at which the ice is forming.

"The water drawn in by the growing crystals of ice will come first from the largest of the unfrozen pores. As these become emptied the supply will be restricted and the rate of growth of the ice will be checked. The evolution of latent heat will not then be sufficient to maintain the temperature constant at the point of ice-formation and the temperature will begin to fall once more.

"As there is then little or no water in the largest pores in the concrete immediately below the first ice layer, freezing will not begin again until the cold front has penetrated some distance, that is, until either the temperature has dropped sufficiently to freeze the pores that do contain water or a level is reached where the larger pores are not affected by the ice forming above them. The result of this process is that the concrete will contain a series of planes of weakness parallel to the surface of cooling. During subsequent cycles of freezing the ice will again tend to form at the same levels as before because the pores there have been distended by the previous ice, and the freezing-point of the water in them will be higher than in the surrounding concrete.

"The damage to the concrete is considered to be caused, not so much by the actual initial increase of volume of the water in the pores on freezing, as by the growth of the crystals afterwards and the consequent segregation and concentration of the ice into the layers."

Further information from Collins' report (3) indicates that the period of ice formation is from -3°C (26.6°F) to -4°C (24.8°F), this being established from a dilatometer test.

The following evidence is in support of the Collins hypothesis.

a) Considerable field data shows that damage is caused by the freezing of water within the material rather than by low temperatures alone. Thus, failure is found only in damp places.

b) Concrete damaged by frost has a laminated appearance. Crystals of ice have been observed beneath the scaled surface of damaged concrete.

c) Laboratory tests demonstrating the difference between wet and dry freezing show a steady reduction in strength of concrete frozen wet, while concrete frozen dry continues to increase in strength.

d) Laminations have been observed in laboratory specimens that were frozen on one end, while the sides were insulated. The opposite end was in contact with unfrozen water. The damage was severe when low quality concrete of high porosity was used. The laminations resembled those found in frost heaving soils.

e) One cycle of freezing of a saturated cylinder in contact with unfrozen water increased the moisture content by 40 grams.

Powers (8) has produced a working hypothesis in which he describes his opinions on the mechanism of concrete destruction by frost. His hypothesis is based on the premise that the destruction of concrete by frost is caused not by direct ice crystal pressure but by the generation of hydraulic pressures in the capillaries and pores. These pressures are built up when water, which is next to the surface being frozen, is forced through the capillaries and pores. The frictional resistance of this flow gives rise to the hydraulic pressures. When the hydraulic pressures exceed the tensile strength of the paste the pore walls are ruptured.

McNeese (6) performed a series of tests designed to answer the following questions:

a) Under what conditions is freshly placed concrete damaged by freezing?

b) How much is it damaged when frozen at various intervals and temperatures?

c) Can concrete be frozen while plastic without damage to its final strength?

From his results he forms the following conclusions:

1. A definite relation holds between loss of compressive strength due to freezing and (a) the time it is frozen after being placed and (b) the temperature at which it is frozen.

2. Loss of strength varies up to 50 percent of the standard, which tends to be a maximum loss for freezing in this manner.
3. If the concrete is placed at 75°F it must be subjected to severe freezing within six hours for any appreciable damage.
4. If it is placed at 40°F, even a mild freezing temperature of 25°F may destroy 50 percent of its strength.
5. Once concrete is frozen through, neither the temperature to which it is reduced, nor the length of time it is subjected to freezing temperatures, greatly affect its strength.

II DESIGN OF EXPERIMENT

The experiment was set up for the purpose of determining the effects of freezing on concrete 0, 1, 3 and 7 days old. Two different temperatures were used:- 25°F and 15°F. These temperatures represent moderate and severe conditions for the Montreal area.

It was desired also to determine the effects of varied lengths of freezing. Consequently cylinders were to be removed after 1, 2, 3 and 4 days freezing. Tests were arranged so that the compressive strengths could be determined at 2, 7 and 28 days after removal from the refrigerator.

Therefore, the following symbols were chosen to represent the periods shown.

t_1 = time elapsed between molding the cylinder and entering the refrigerator box.

t_2 = time elapsed in refrigerator.

t_3 = time elapsed between removal from the cold box and testing.

θ_1 = high temperature 25°F

θ_2 = low temperature 15°F

The variables were set up as follows:

t_1 = 0 1 3 7 days

t_2 = 1 2 3 4 days

t_3 = 0 2 7 28 days

θ_1 = 25°F

θ_2 = 15°F

This gave 128 tests to be made. In addition it was required to have control cylinders for 1, 3, 7, 14 and 28 day tests. Each test consisted of three cylinders.

The lettering or marking of the cylinders was done in the following manner.

1. The prefix A, B, C, D or a, b, c, d, stood for t_1 i.e. 0, 1, 3 or 7 days. The capital letters meant θ_1 (25°F) and the lower case letters stood for θ_2 (15°F).
2. The secondary numeral, i.e. 1, 2, 3 and 4, stood for t_2 in days.
3. The last numeral, i.e. 0, 2, 7 and 28, stood for t_3 in days.

   Example:

   A cylinder marked B 3 7 would be air cured for one day and would then enter the cold box. It would remain in the cold box for three days at 25°F. Upon removal, it would be thawed out and then stored in the curing bath for seven days. On the seventh day the cylinder would be capped and then tested.

The schedule of operations was set up and followed as shown in Table I.

TABLE I

SCHEDULE OF OPERATIONS

DATE	MOLD	REFRIGERATOR		CURE	TEST
		IN	OUT		
		Temp 25°F			
0					
1	A1, B4	A1			
2	A2	A2, B4	A1		A10
3				A1	
4	A3	A3	A2		A20, A12
5	B3			A2	
6	C4	B3	B4		B40, A22
7	A4	A4	A3	B4	A30
8	C1			A3	B42
9	C2, D3	C4	B3		B30, A32, A17
10	C3, D4			B3	
11		C1	A4		A40, B32, A27
12	D2	C2	C1	A4	C10
13	B1	C3	C4	C1	C40, A42, B47
14	B2, D1	B1	C2	C4	C20, C12, A37
15		B2	B1	C2	B10, C42
16		D3	C3	B1	C30, C22, B37
17		D4	B2	C3	B20, B12
18				B2	C32, A47
19		D2	D3		D30, B22, C17
20				D3	C47
21		D1	D4, D2		D40, D20, D32, C27
22			D1	D4, D2	D10, B17
23	b4	Temp 15°F		D1	D42, D22, C37
24	a4	b4, a4			D12, B27
25	c1				
26	c4				D37
27					
28	a3	c1, a3	b4, a4		D47, D27, b40, a40
29	d1	c4	c1	b4, a4	D17, c10
30	b3			c1	A128, b42, a42
31	d4	b3	a3		a30, c12
32	b2			a3	A228
33		b2	c4		c40, a32
34	a2	a2	b3	c4	B428, b30, c42
35			b2	b3	A328, b20, b47, a47

TABLE I (Continued)

DATE	MOLD	REFRIGERATOR IN	OUT	CURE	TEST
36	b1,*T28	d1	a2	b2	a20, b32, c72
37		b1	d1	T28	B328, d10, b22
38		d4	b1	d1	b10, a22, a37
39					A428, d12
40					b12, c47, C128
41					b37, C428
42	T14,T3		d4		b27, d40, C228
43	a1	a1		d4	a27, B128
44	T7		a1	T3,T14	a10, d42, d17, C328
45					b17, B228, T3
46					a12
47					D328
48					
49					d47, D428, D228
50					D128
51					a17, T7
52					
53					
54					
55					
56					b428, a428, T14
57					c128
58					
59					a328
60					
61					c428
62					b328
63					b228
64					a228
65					d128
66					b128
67					
68					
69					
70					d428
71					
72					a128

* Sumbol "T" stands for control cylinders.

III MATERIALS USED IN TESTS

1. Cement:

The cement was normal portland cement supplied by the Canada Cement Company Limited, Montreal. All of the cement was from the same batch and was free of lumps. Its setting times were:

Initial: 3 hours, 20 minutes

Final: 6 hours, 10 minutes

2. Water:

Montreal city tap water is used by the concrete construction industry in Montreal. It was also used for this experiment.

3. Aggregates:

a) Sand:

The sand was from St. Gabriel de Brandon, P.Q. This sand is used commercially for concrete in the Montreal area. The mechanical analysis of this sand is shown in Table II.

b) Coarse Aggregate:

Miron et Freres Ltee. supplied the coarse aggregate. It was quarried and crushed at their plant in Montreal. This aggregate, a limestone, is used extensively in the Montreal area. Its mechanical analysis is shown in Table II.

The mechanical analysis of both aggregates are plotted in Figure 1. The C.E.S.A.-A23-1942 limits are also shown. The graph illustrates that the sand contained a fairly large amount of +4 mesh.

TABLE II

Characteristics of the Fine and Coarse Aggregates

PASSING	HELD ON	Percent by Weight: COARSE AGG.	FINE AGG. Whole Sample	FINE AGG. -4 Mesh
1"	3/4	6.9		
3/4	1/2	37.0		
1/2	3/8	22.2	4.6	
3/8	No 4	29.1	8.8	
No 4	8	3.1	9.7	11.2
8	16	1.7	14.0	16.2
16	30		21.6	25.0
30	50		30.0	34.6
50	100		9.3	10.7
100	200		2.0	2.3
200	-		0.0	0.0
Totals		100.0	100.0	100.0
Fineness Modulus			2.91	2.76
Humus, p.p.m.			Nil	

4. Mixer:

The mixer shown in Figure 2 was made by the London Machinery Co. It had a capacity of two cubic feet and was powered by a 3/4 H.P. electric motor that rotated the mixing bowl at 40 R.P.M.

5. Scale:

The scale used for weighing the aggregates etc., was a platform scale constructed by the Fairbanks-Morse Co. It was accurate to one-tenth of a pound.

6. Cylinder Moulds:

These were purchased from the Cleveland Container Co. and were manufactured in Toronto. They were triple layer pasteboard parafin coated. The ends were not the metal type. They were six inch inside diameter and twelve inches high.

7. Refrigerator:

The cold box was constructed at McGill in 1954 and was adapted for this experiment. Figure 3 shows a bird's eye view of the box with its top removed. The large top of the box was removed by an electric hoist to facilitate the entrance of the cylinders resting in their racks.

The freezing unit was of one and one half ton capacity and used freon as a refrigerant. Regulation of the temperature was done by a Minneapolis-Honeywell thermostat. Circulation within the cold box was provided by a 1/32 H.P. four inch rubber bladed fan mounted in a lower corner.

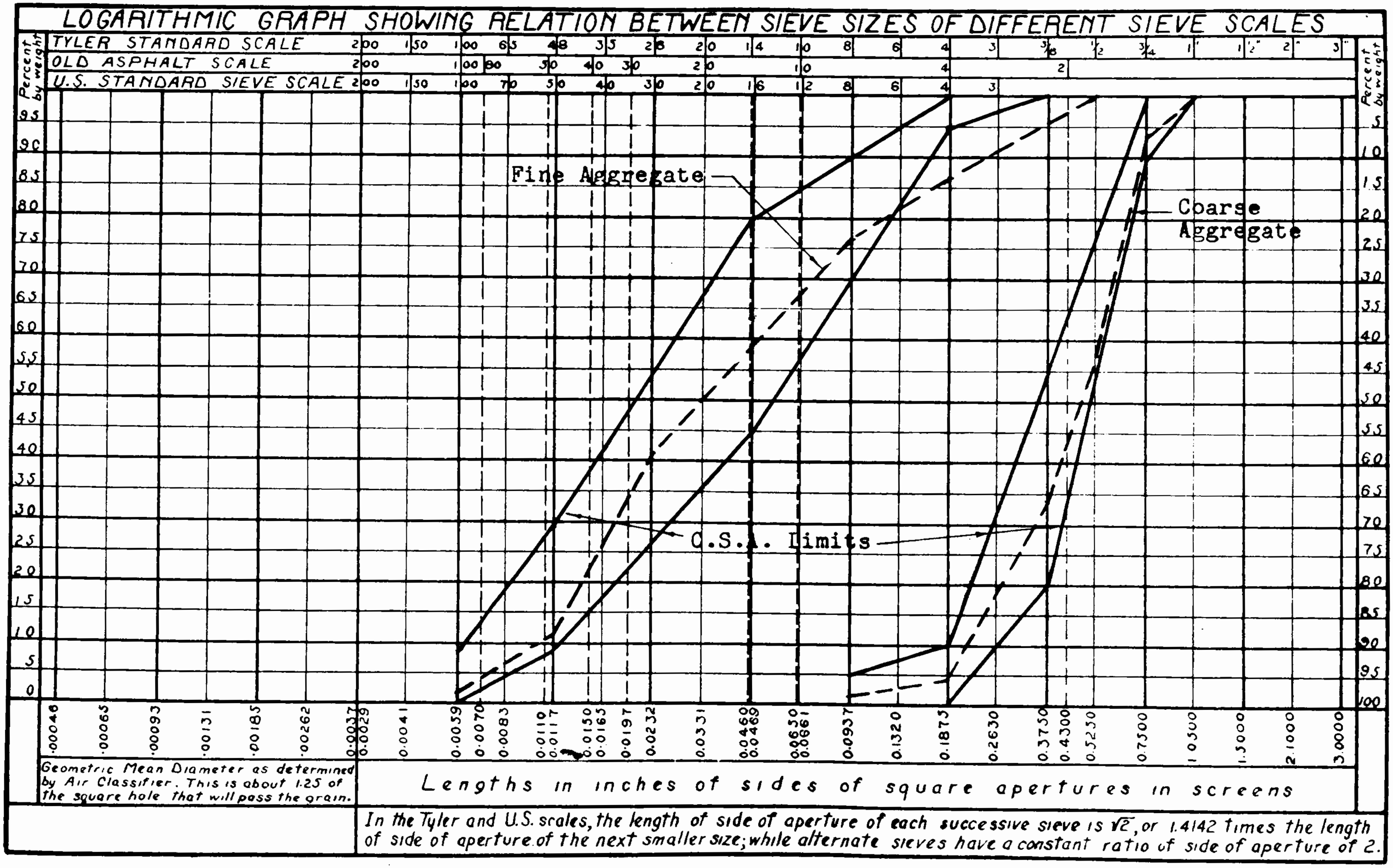


Fig. 1. Mechanical Analysis of Aggregates.

Figure 2. Moulding of the specimens

Figure 3. View showing the interior of the refrigerator.

8. Temperature Measurement Apparatus:

A Leeds and Northrop Co. potentiometer was used to measure the e.m.f. produced by six copper-constantan thermocouple wires. This potentiometer was in good condition. It had a built-in galvanometer that was accurate enough to give results to the closest degree Fahrenheit. This was accurate enough for this investigation. It had a device which enabled the operator to adjust on a dial the millivolt reading of the reference junction, and by so doing it was possible to read directly the millivolts corresponding to the unknown junction.

The copper-constantan wires had their ends tinned, entwined, and then soldered. Some engineers fuse the ends with a torch, but the above method used was found satisfactory. One end of each thermocouple was placed in the reference junction bath and the other end passed through the wall of the cold box to its respective place within. There were six thermocouples, two for each layer of cylinders. A switch box facilitated the readings. The reference junction was a double walled quart vacuum bottle filled with water. The temperature was measured with a Hatton-Garden thermometer. It registered from 0 - 100°F and was accurate to 1/10 of a degree.

9. Capping Machine:

The capping machine had been manufactured by the Tinius Olsen Company. It held the cylinder by means of two steel straps while the 1/8 to 1/4 inch spaces between the two parallel ends of the cylinder were filled with capping compound. The machine was old but still serviceable. It is seen in Figure 4.

10. Capping Material:

The material used for capping the ends of the cylinders was a sulphur-fly ash compound named Haymanite Cement. It is also used for jointing water mains.

11. Testing Machines:

Two different testing machines were used. The majority of the cylinders were broken in the 220 ton Baldwin Tate Emery machine, shown in Figure 5. The remainder were tested in a Yale and Towne machine of 75 ton capacity.

Figure 4. Capping the Cylinders.

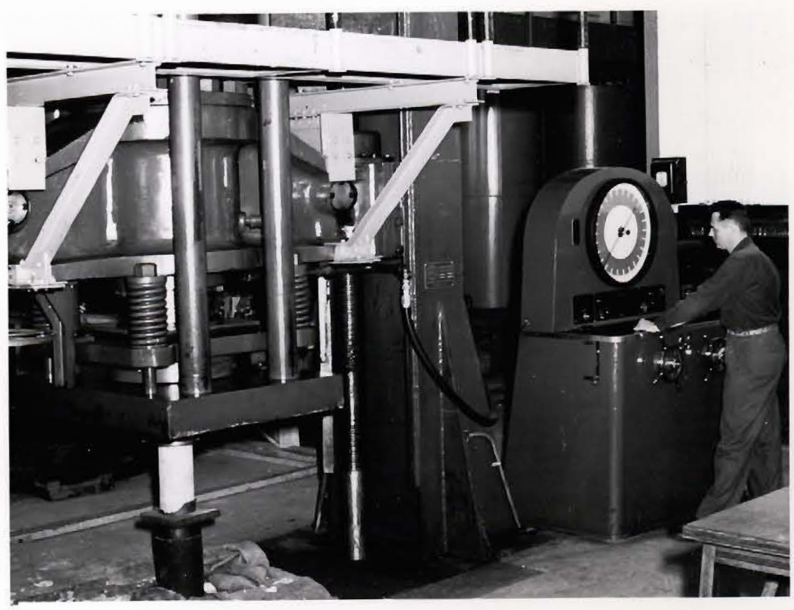


Figure 5. The Baldwin Tate Emery testing machine.

IV PROCEDURE

1. Weighing and Batching

The concrete constituents were placed in clean metal pails for weighing. After weighing, the aggregates, etc., were placed in the mixer in the following order:- coarse aggregate, sand, cement, and finally the water.

2. Mixing:

The aggregates and cement were dry mixed for 30 seconds before the water was added. Only enough water was added to bring the slump to between one and two inches. When the mixing was completed the concrete was dumped into a 2' x 3' x 6" deep metal pan.

3. Moulding of Specimens:

Slump testing and the moulding (see Figure 2) of the cylinders were carried out in accordance with C.E.S.A. specification A23-1942 clauses 25A and 248(a) respectively, with the exception that after striking off the excess concrete from the top layer of the cylinder mould, no plate covered the surface. In the case of the specimens to be frozen immediately, i.e. the "A" and "a" series, it would have been impracticable to have the surface covered. Accordingly, the remaining cylinders were treated in the same manner.

Care was exercised in rodding the first layer of concrete, so as not to penetrate the parafin coating of the base of the paper moulds.

4. Transporting Specimens:

The concrete for the specimens was mixed in the soils and concrete laboratory in the basement of the Macdonald Engineering Building at McGill University. The specimens were moulded there also. After moulding, the cylinders were carried up to the ground floor and deposited on a small dolly. They were then wheeled into the refrigerator room.

NOTE: The above applies only to the "A" and "a" specimens, i.e. cylinders to be exposed to freezing immediately after moulding. The others remained in the laboratory air curing, until it was time for them to enter the refrigerator.

5. Freezing of Specimens:

To facilitate entry and exit of the cylinders into the refrigerator, two racks were built (see Figure 6.) each holding twelve cylinders. The racks were filled at floor level, raised by an electric travelling hoist, rolled forward above the refrigerator and lowered into the freezing compartment. The same hoist was then used to lift the heavy insulated lid into place.

6. Temperature Regulation:

Immediately following the placing of the top of the cold box, the small circulating fan was turned on. A twice daily check of the temperature within the refrigerator was carried out with the thermocouples. Regulation of the temperature was done with a Minneapolis-Honeywell thermostat.

7. Curing:

Upon removal from the cold box, cylinders not being tested immediately were kept in air at 68° - 70°F for 24 hours. At this time, they were stripped of their moulds and were entered into a water bath whose temperature was 70°±2°F. The cylinders were removed from the bath about two days before the time of testing for capping purposes. They were re-entered in the curing bath after capping, and remained there until the time of the test.

8. Capping:

The parallel end blocks of the capping machine were oiled to prevent the adhesion of the capping material to them. The cylinder was then laid in the machine, and held in position by the steel straps provided for that purpose. The movable end block was adjusted horizontally so that the end spaces were about 3/16 of an inch. The liquid Haymanite was then poured into the appropriate spaces, thus forming the cap. The cylinder was removed after one minute.

9. Testing Specimens:

The testing of the cylinders was carried out in accordance with the C.E.S.A. specifications A23-1942 clauses 237 and 238. The ultimate compressive strength was recorded. Visual examination showed whether or not frost lines were in evidence.

V OBSERVATIONS AND RESULTS

1. The weigh scale, for batching the aggregates worked satisfactorily.
2. The mixer was slightly loaded with old concrete. An attempt was made to remove this by running the machine with large pieces of iron in the mixer bowl. This was not successful. Difficulty was encountered from the above in emptying the mixer bowl. Due to the relatively stiff mix it was necessary to remove the last part of each batch by hand.
3. The moulding of the concrete specimens was accomplished with comparitive ease.
4. Some difficulty was encountered lowering the racks into the cold box when they were filled with specimens still in their moulds. Specimens frozen immediately had to have their moulds left on for the duration of the freezing period.
5. The mechanical portion of the cold box performed very well. The compressor unit, of one and one half tons capacity, was more than ample for the job. After opening the cold box to change cylinders, the ambient temperature of 15°F could be reached once more within ten minutes after replacing the lid.

6. The six thermocouples used for measuring the ambient temperatures gave true and consistent results. They showed that the regulator cut the compressor in when the temperature became about 2 degrees above the required degree of cold.

7. The capping process proved to be quite difficult and time consuming. The problems were:-

   a) It took about 25 minutes to liquify the capping compound.

   b) During this 25 minutes and after, a nauseating smoke was emitted from the pot containing the capping compound. The lack of air conditioning made the situation much worse than it need have been.

   c) The capping machine was quite old, and a clamp for holding one of the end blocks was broken. This allowed a possibility that the capping ends were not always parallel. However, the machine, method and materials provided a good testing surface in accordance with the C.E.S.A. specification A23-1942 Clause 249(b).

8. The curing tank was easily accessible and spacious. The curing water temperature was always between 68° and 70°F in accordance with C.E.S.A. A23-1942 Clause 250(b).

9. The majority of the specimens were crushed in the 220 ton Baldwin Tate Emery testing machine. The remainder were tested with a Yale and Towne machine of 100 ton capacity. Both machines performed very well with the rate of loading at approximately 35 p.s.i. per second.

Figure 6. Lowering of the cylinders into the cold box.

Figure 7. Rupture of the mortar in frozen concrete.

10. Results of the Experiment:

The "A" and "a" series were plastic when thawing began after removal from the cold box. It was found by examination of the "A" and "a" - 2, 7 and 28 day cylinders, that rupture of the mortar had occurred, particularly at the underside of the coarse aggregate. See figure 7 for typical appearance of freeze lines in concrete damaged by frost.

The cylinders that had had air curing of 24 hours or more prior to freezing did not show any signs of frost damage when examined after crushing.

Tables III and IV give the crushing strength of all the cylinders. Figures 8. to 11. show the average results in graph form.

The temperature at the center of a concrete cylinder fell below 32°F, in approximately (a) eleven hours when subjected to a temperature of 25°F, and (b) eight hours when exposed to air at 15°F. Figure 12 illustrates the rates of cooling at the centers of cylinders when they are exposed to air at 25° and 15°F.

TABLE III - Compressive Strengths of 6" x 12" Cylinders Frozen at 25°F.

Series	Exposure Time Days	Time After Exposure Until Testing - Days: 0		2		7		28	
A*	1			1040		1750		2960	
		0		1510	1340	1850	1810	2910	2910
				1480		1830		2860	
	2			1170		1400		1950	
		0		1780	1170	1530	1500	2360	2290
				1170		1580		2550	
	3			1030		1600		2560	
		0		1150	1330	1670	1600	3150	2790
				1810		1520		2660	
	4			-		1830		2450	
		0		1380	1360	1830	1690	2670	2550
				1330		1420		2530	
B	1	1490		2020		2700		4510	
		1440	1480	2160	2040	3300	2980	4400	4310
		1520		1950		2940		4010	
	2	1280		2720		3690		4400	
		1600	1420	2640	2710	3610	3530	4340	4350
		1380		2780		3300		4300	
	3	1540		-		3180		3900	
		1540	1570	2060	2230	3010	3100	4200	4000
		1630		2400		-		3900	
	4	1540		1810		2700		4060	
		1380	1340	1950	1910	-	2740	3910	3840
		1080		1980		2770		3550	
C	1	2200		2700		3290		2760	
		2420	2380	2900	2800	3110	3200	4050	3900
		2500		-		-		-	
	2	2320		2430		3160		3480	
		2040	2160	2450	2450	2900	2890	3400	3640
		2120		2470		2610		4040	
	3	2190		2380		2750		-	
		2220	2210	2760	2650	2860	3010	3700	3750
		2210		2820		3410		3800	
	4	2210		2730		3000		4250	
		2210	2340	2450	2700	3250	3280	4080	4160
		2600		2900		3600		4150	
D	1	2860		2660		3610		3490	
		2790	2940	3260	3040	3580	3340	3490	3600
		3160		3200		2840		3810	
	2	2970		3050		3050		3480	
		2740	2900	2960	2950	3410	3190	3610	3540
		3000		2840		3100		3520	
	3	2750		2980		3200		3580	
		-	2830	2800	2960	3260	3160	3710	3710
		2910		3110		3030		3850	
	4	2980		3000		2960		3170	
		2790	2760	2870	2940	3000	3060	3580	3460
		2900		2940		3210		3630	

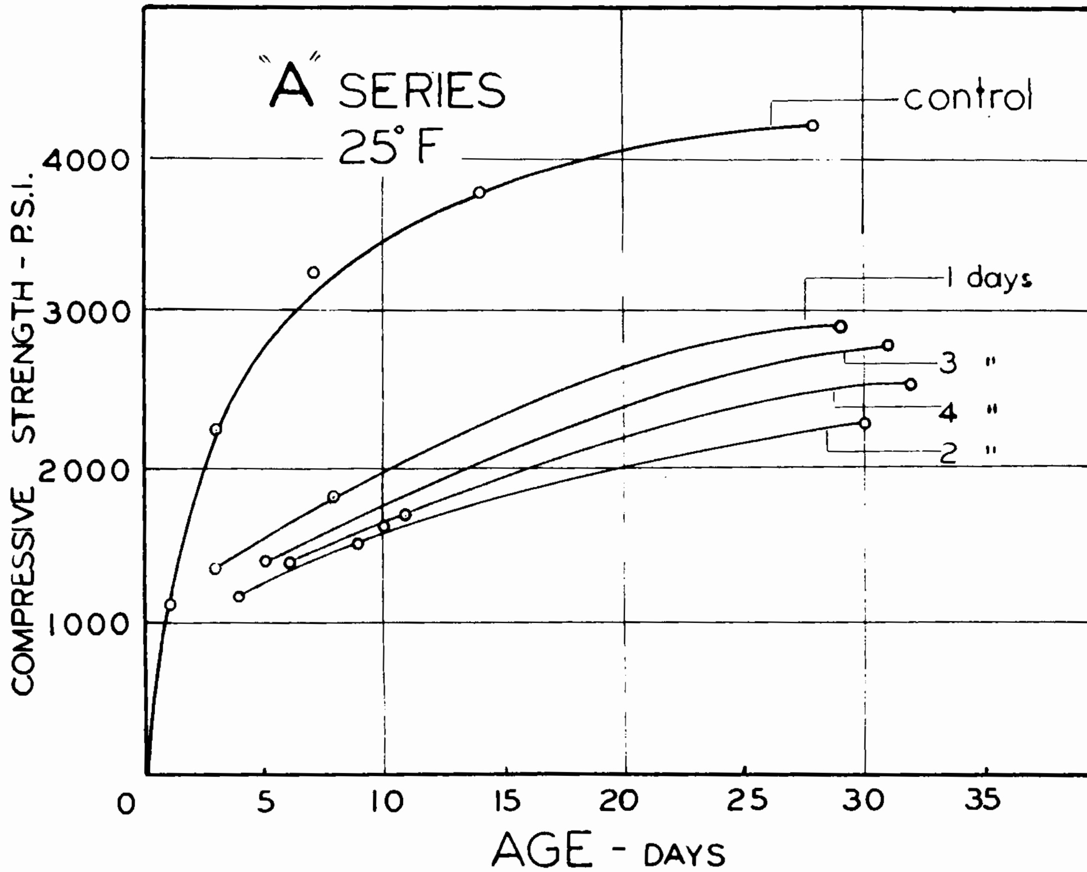
* "A" Series air cured 0 days before exposure.
"B" " " " 1 " " "
"C" " " " 3 " " "
"D" " " " 7 " " "

TABLE IV - Compressive Strengths of 6" x 12" Cylinders Frozen at 15°F

Series	Exposure Time Days	Time After Exposure Until Testing - Days: 0		2		7		28	
a*	1		0	1430 1470 1500	1470	2000 1970 2080	2020	3040 2910 2710	2890
	2		0	1240 1170 1160	1190	1980 1820 1900	1900	2480 2430 2270	2390
	3		0	1150 960 1170	1090	1770 1710 1570	1680	2660 2690 2560	2640
	4		0	980 1240 1100	1100	1580 2100 1630	1770	2440 3250 2810	2830
b	1	1600 1310 1490	1470	2500 2500 2520	2500	3510 3400 3760	3560	4180 3810 4150	4050
	2	1810 1700 1720	1740	2020 2120 2590	2240	2970 3160 3590	3240	4280 4300 4150	4240
	3	1780 1700 1580	1690	2320 2340 2320	2320	2900 3300 3510	3230	4180 3910 3900	4000
	4	1420 1470 1520	1470	2610 2540 2800	2650	3600 3690 3460	3580	4210 4430 3840	4160
c	1	2110 2160 2260	2180	2710 2710 2660	2690	3140 2980 3150	3090	3900 3720 3570	3730
	4	2200 2370 2280	2280	3130 3020 2880	3010	3340 3410 3300	3350	3980 4200 4000	4060
d	1	3090 2880 3050	3010	3050 3060 2960	3020	3460 3210 3550	3440	3600 3740 3300	3550
	4	3240 3020 2900	3050	3320 3170 3110	3200	3530 3530 3290	3450	3810 3750 3810	3790

* "a" Series air cured 0 days before exposure
"b" " " " 1 " " "
"c" " " " 3 " " "
"d" " " " 7 " " "

Figure 8.


"A" SERIES
25°F
control
1 days
3 "
4 "
2 "
COMPRESSIVE STRENGTH - P.S.I.
4000
3000
2000
1000
0
5
10
15
20
25
30
35
AGE - DAYS

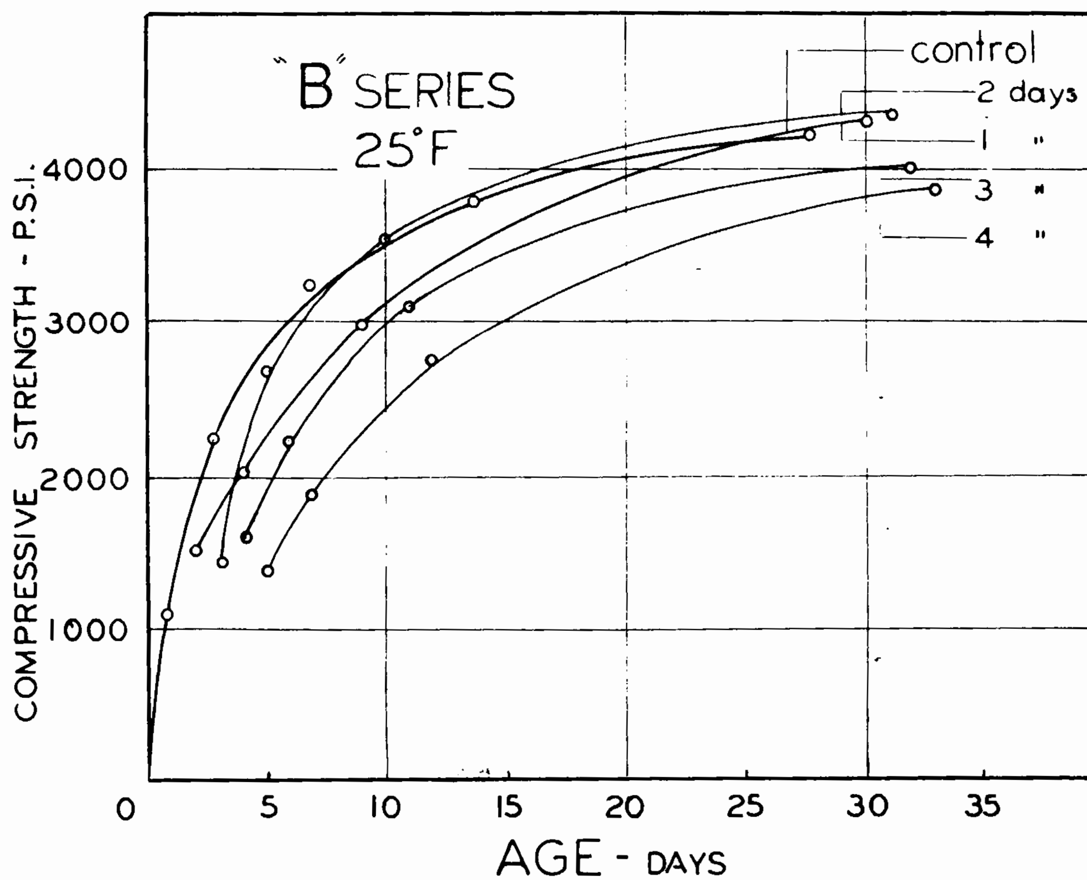
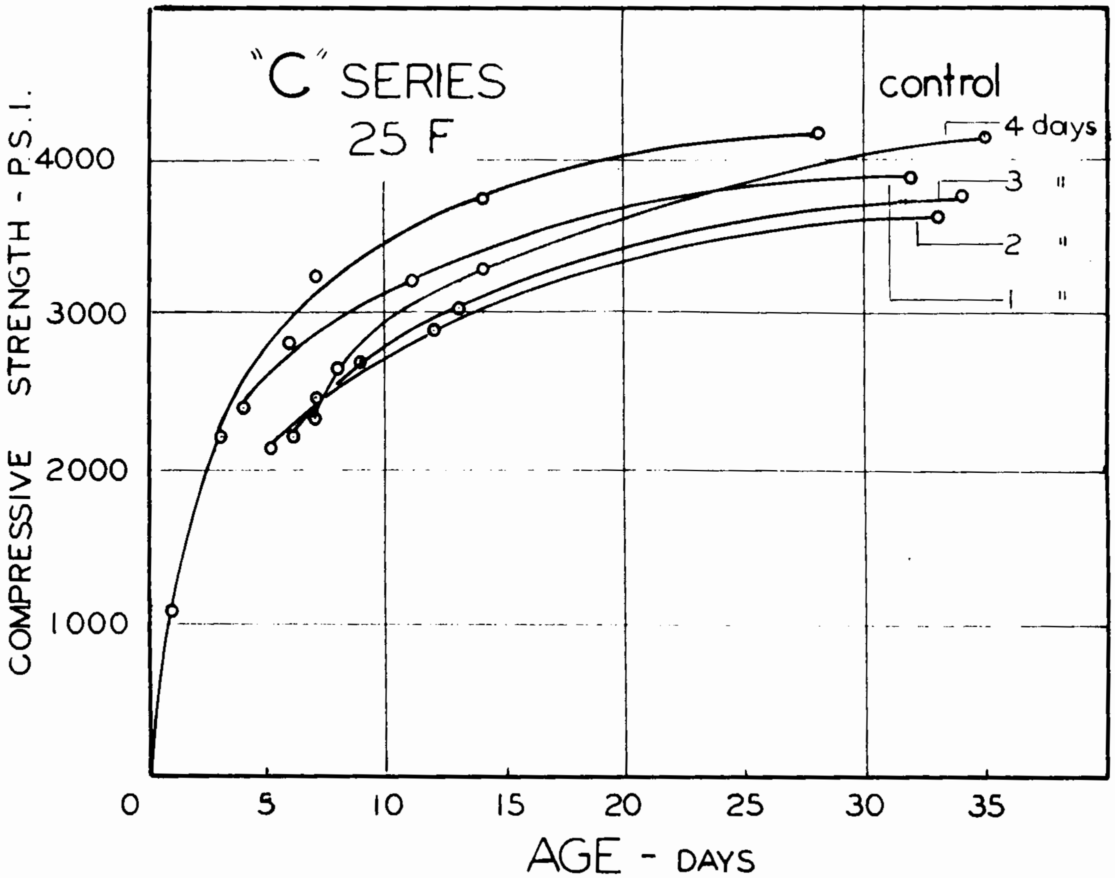

"B" SERIES
25°F
control
2 days
1 "
3 "
4 "
COMPRESSIVE STRENGTH - P.S.I.
4000
3000
2000
1000
0
5
10
15
20
25
30
35
AGE - DAYS

Figure 9.


"C" SERIES
25 F
control
4 days
3 "
2 "
1 "
COMPRESSIVE STRENGTH - P.S.I.
4000
3000
2000
1000
0
5
10
15
20
25
30
35
AGE - DAYS

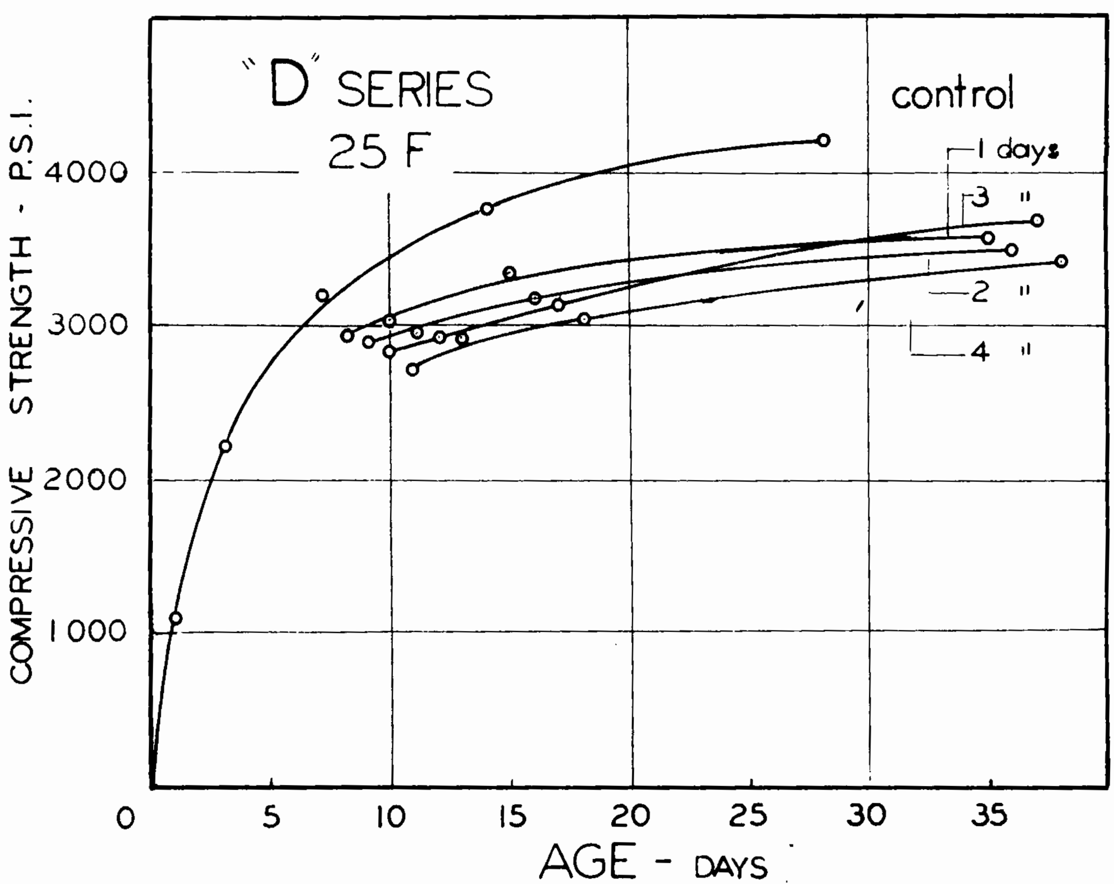
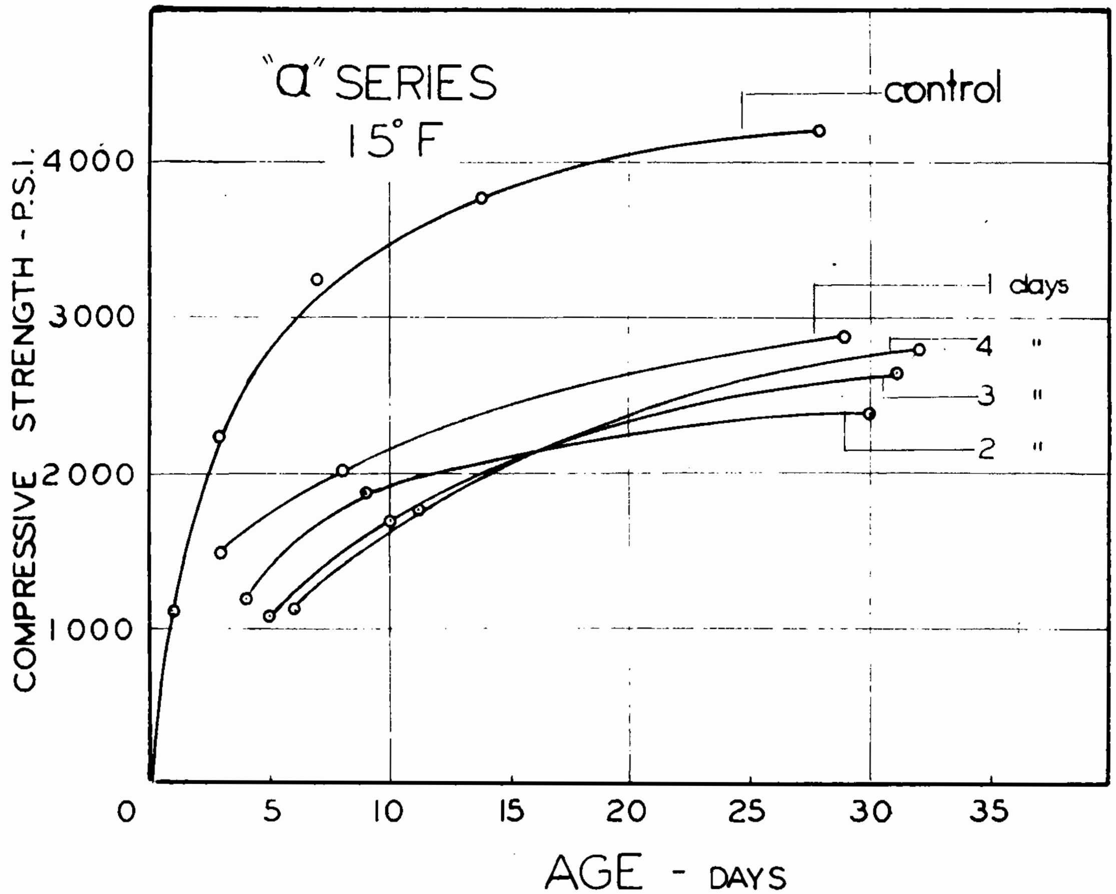

"D" SERIES
25 F
control
1 days
3 "
2 "
4 "
COMPRESSIVE STRENGTH - P.S.I.
4000
3000
2000
1000
0
5
10
15
20
25
30
35
AGE - DAYS

Figure 10.


"a" SERIES
15° F
control
1 days
4 "
3 "
2 "
COMPRESSIVE STRENGTH - P.S.I.
4000
3000
2000
1000
0
5
10
15
20
25
30
35
AGE - DAYS

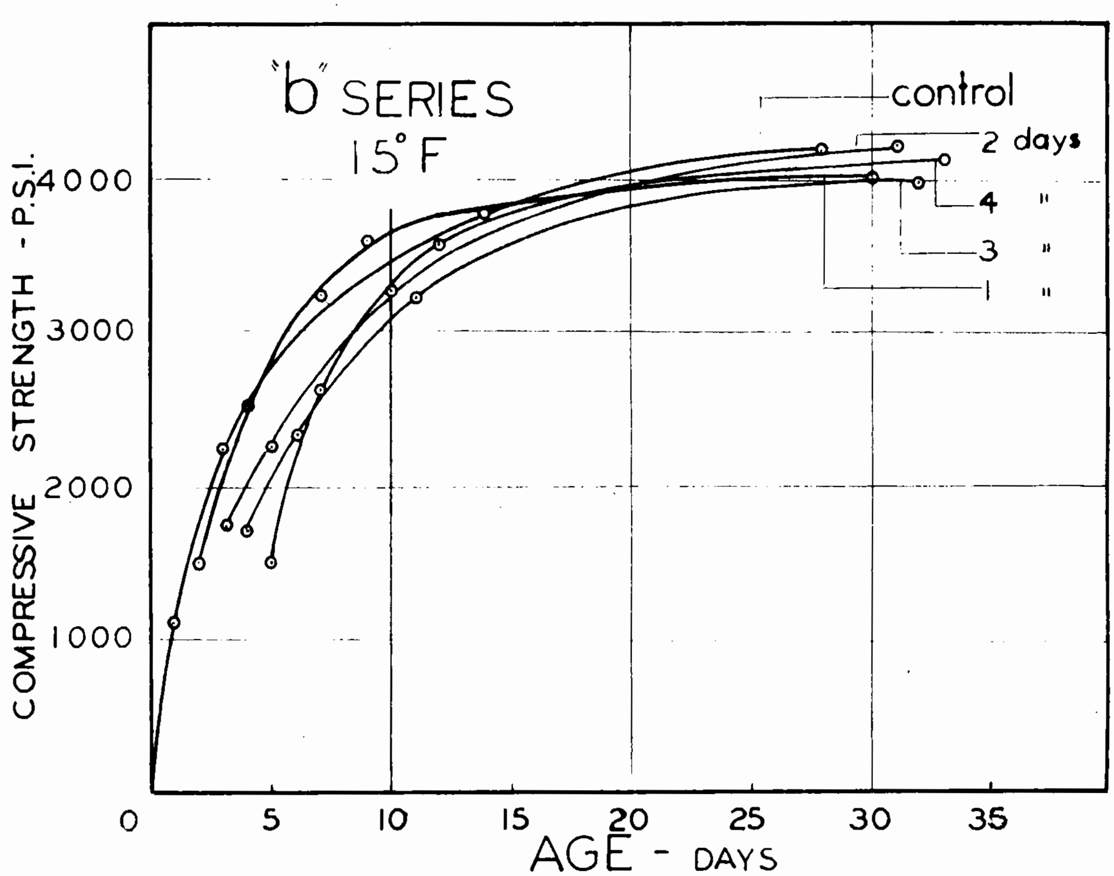
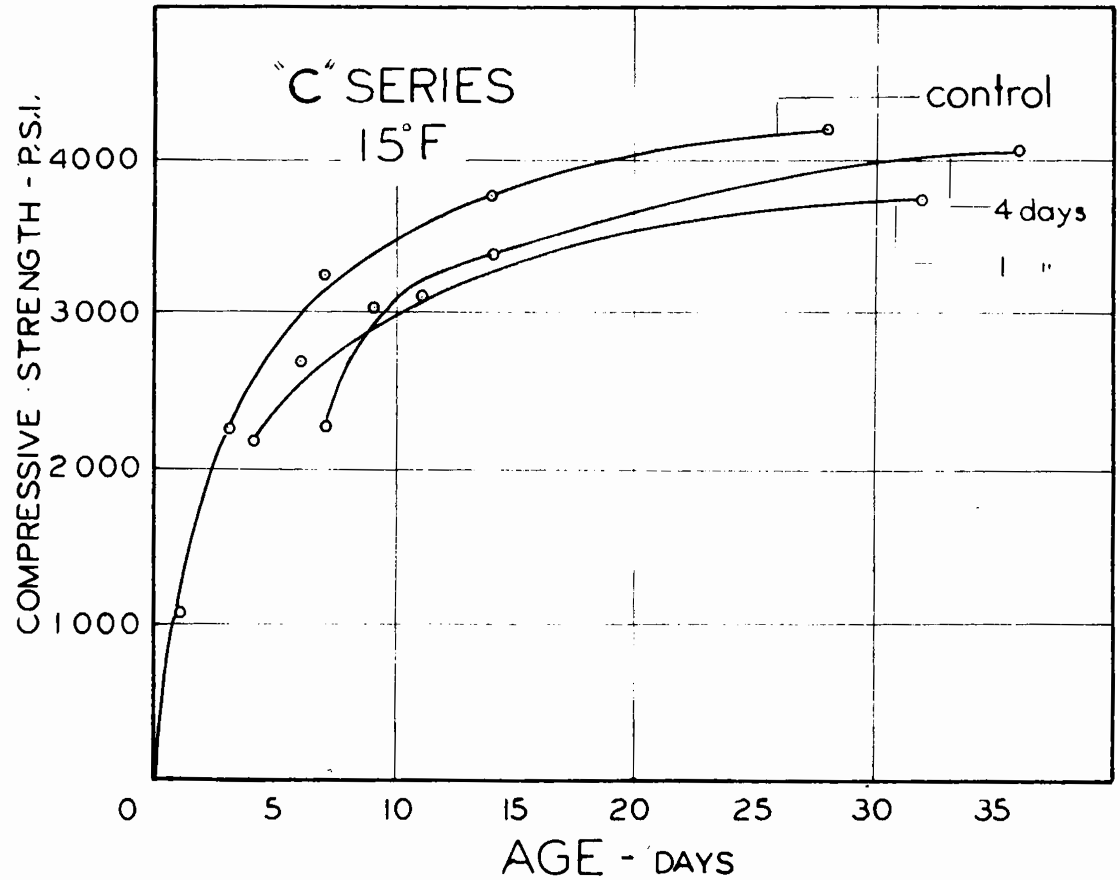

"b" SERIES
15° F
control
2 days
4 "
3 "
1 "
COMPRESSIVE STRENGTH - P.S.I.
4000
3000
2000
1000
0
5
10
15
20
25
30
35
AGE - DAYS

Figure 11.


"C" SERIES
15°F
control
4 days
1 "
COMPRESSIVE STRENGTH - P.S.I.
4000
3000
2000
1000
0
5
10
15
20
25
30
35
AGE - DAYS

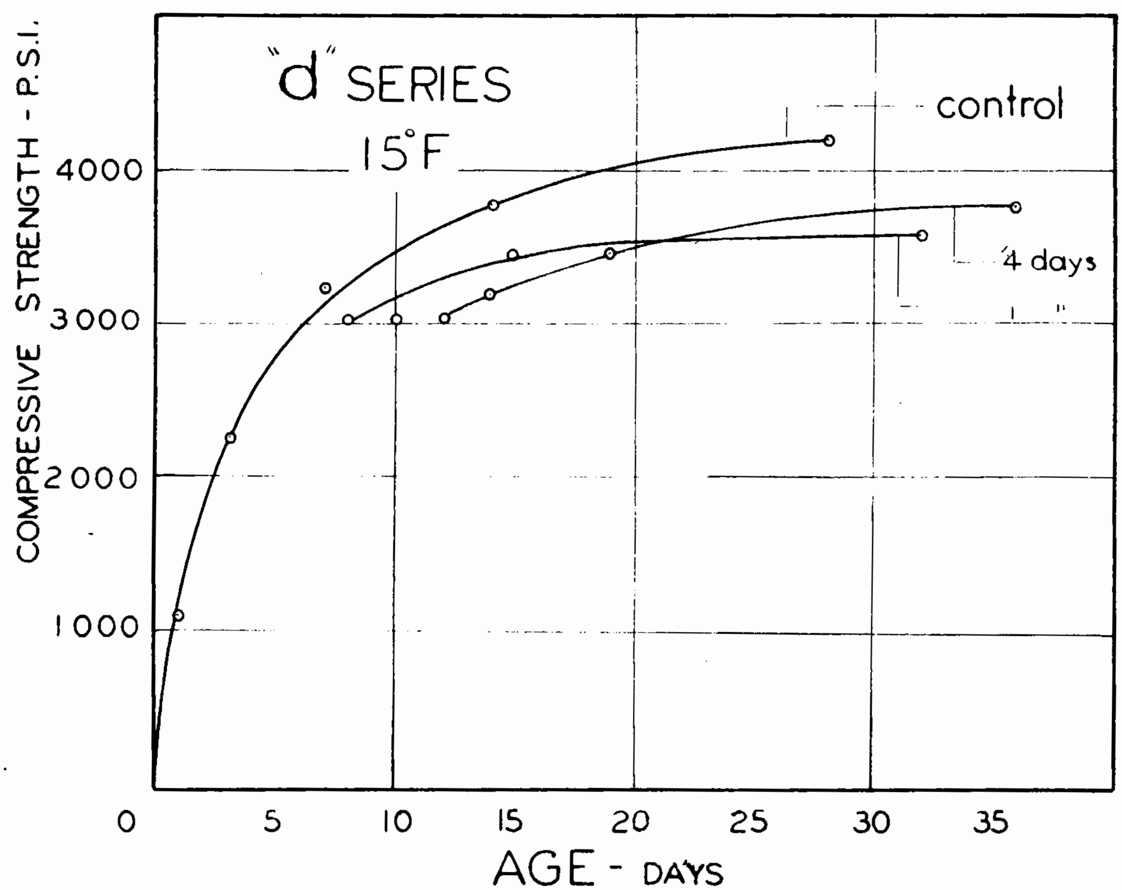
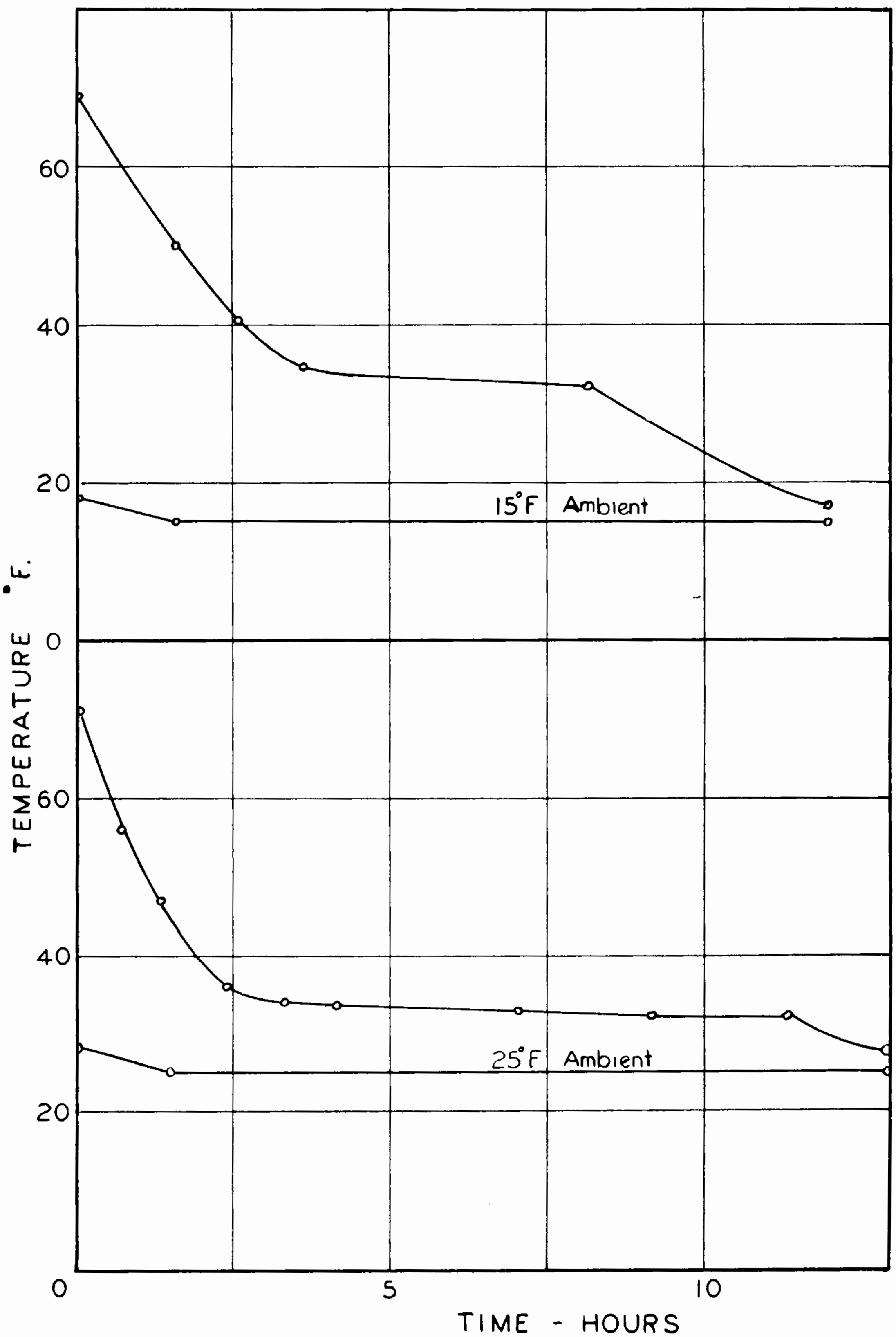

"d" SERIES
15°F
control
4 days
1 "
COMPRESSIVE STRENGTH - P.S.I.
4000
3000
2000
1000
0
5
10
15
20
25
30
35
AGE - DAYS

Figure 12. - Cooling rates at the center of 6" x 12" cylinders.



VI CONCLUSIONS

The "A" series frozen immediately at 25°F suffered an average compressive strength loss of 1570 p.s.i. or 37.5 percent. The maximum loss was 1910 p.s.i. or 45.5 percent, and the minimum was 1290 p.s.i. or 31 percent.

The "a" series frozen immediately at 15°F showed an average loss of 1520 p.s.i. or 36 percent. The maximum 1310 p.s.i. or 43 percent, and the minimum 1310 p.s.i. or 31 percent.

The "B" series frozen at 25°F after one day air curing showed an average loss of only 80 p.s.i. or 2 percent which cannot be considered as significant.

The "b" series similarly showed a very small loss.

The apparent loss of compressive strength of the "C" and "c" series is not due to freezing, but rather to the effect of air than moist curing during the wait to be entered in the refrigerator*. The average loss of strength for the "C" series was 8 percent and for the "c" series 7 percent. Bloem (2) found that the differential in strength between three day cylinders of which one set was air cured, and the other moist cured after one day, was 13 percent. Therefore, if the series "C" and "c" were 13 percent lower at 3 days, it is a reasonable assumption that post-freezing curing for 28 days would bring their strengths up to within 7 percent of the control cylinders.

* The reason for air curing the cylinders before freezing was to simulate the usual conditions on small jobs. The author has observed that it is common practice to provide no curing after placing of winter concrete.

Similarly the losses found with the "D" and "d" series were caused by air curing prior to the freezing period. Bloem (2) also found, for the similar conditions as above, for 7 days the differential was 24 percent. As with the "C" and "c" series, the "D" and "d" series narrowed the loss down from 24 percent to between 12.5 and 15 percent.

The time required for the cooling of the cylinders from the mixing temperature of 70°F to approximately 32°F was nearly the same as the time required for the initial set of the cement to take place. However, no significance can be attached to this phenomena due to the paucity of tests pertaining to it.

Referring to Figure 12, it is seen that the cooling curves become nearly horizontal at, or slightly above 32°F for a duration ranging from 4 to 10 hours, depending on the ambient temperature. This is the period during which the available water in the concrete is frozen and the temperature of the aggregate is being lowered. Not all the water in the concrete has turned to ice below 32°F due to the pressures that develop from the cold front moving towards the center from the exterior surfaces. The expansion of the freezing water forces the unfrozen water towards the center and consequently pressures develop that require the temperature to fall below 32°F in order to form ice.

The damage resulting from freezing concrete immediately after placing appears to be from the rupture of the mortar. Whether this is caused by (a) expansion of freezing water exerting a disrupting force or (b) hydraulic pressures developed as the ice front, moving towards the center, forces unfrozen water through small capillaries rupturing them in tension, has not been determined. It is probably a combination of both forces. Factors such as water and cement contents, and size and grading of the aggregates may influence the method of distruction.

The results of the experiment suggest the following conclusions:

1. Concrete placed at 70°F and subjected immediately to air at 25° or 15°F is severly damaged. The mortar becomes ruptured, and subsequently the compressive strength is reduced up to 45 percent at 28 days. It is also probable that the durability of the concrete will suffer from the same effect.
2. Low slump concrete (2" or less) cured in air at 70°F for 24 hours before exposure to below freezing air, showed no significant loss of compressive strength at 28 days. Whether the durability to freeze and thaw action had been affected or not must be determined by further tests.
3. The duration of the freezing period has no apparent effect on the compressive strength of the concrete. No significant

losses or gains were noted whether the exposure period was 1, 2, 3 or 4 days.

4. It takes a relatively long time to freeze a concrete cylinder completely through. This is due to (a) the heat of hydration as the cement and water react chemically, and (b) the latent heat given off as water is transformed to ice. Naturally if a wind were present the time would be reduced.
5. Damage was independent of the freezing temperature, whether 25° or 15°F.

From a revue of the literature the following points summarize some of the factors which tend to make cold weather effects on fresh concrete more adverse.

1. Placing of the concrete without protection when the temperature is below 32°F.
2. High slump of the fresh mix.
3. Fast rate of freezing.
4. High moisture content at time of freezing.
5. Low temperature of the mix at time of placing.
6. Low strength concrete.
7. Access to unfrozen water on the side remote from freezing.
8. Adverse curing conditions after freezing exposure.

VII. REFERENCES

1. ALLIN, R.V. and H.H. TURNER, Reinforced portland cement concrete in cold weather.
Cement and Lime Manufacture, v.13, No.11, Nov. 1940.

2. BLOEM, D.L. Effect of curing conditions on compressive strength of concrete test specimens. National Sand and Gravel Assn. Circ. No. 59.

3. COLLINS, A.R. The destruction of concrete by frost. J. Inst. Civil Engineering, No. 1, Nov. 1944.

4. GUNZBURG, A.M. Frozen concrete used in Russian buildings. Engineering News Record, 1931.

5. McDANIELS, A.B. Influence of temperature on strength of concrete. Bull. 81, Univ. of Illinois. Engineering Experimental Station, 1915.

6. McNEESE, D.C. Early freezing of non air entrained concrete. J. American Concrete Institute. v.24, Dec. 1952.

7. MUIR, H.H. Frozen concrete used in Minneapolis. Engineering News Record, 1931.

8. POWERS, T.C. A working hypothesis for further studies of frost resistance of concrete. J. American Concrete Inst. v.16, Feb. 1945.

9. SCOFIELD, H.H. Some tests to show the effect of freezing on permeability, strength and elasticity of concrete and mortars. Proc. American Society for Testing Materials. v.37, 1937.

10. TIMMS, A.G., and N.H. WITHEY, Temperature effects on compressive strengths of concrete. J. American Concrete Inst. Jan., Feb. 1934.
and
Further studies of temperature effects on compressive strengths of concrete. J. American Concrete Inst. Nov., Dec. 1934.

11. Discussion on frozen concrete - Job problems and practice. J. American Concrete Institute, v.14, Nov. 1942.

12. Standard specification for concrete and reinforced concrete. Canadian Engineering Standards Assn. 1942.

13. Recommended practice for selecting proportions for concrete. J. American Concrete Institute, v.26, Sept. 1954.

VIII ACKNOWLEDGEMENTS

The writer wishes to express his thanks to:

Carleton Craig for his valued assistance in planning the tests.

V. W. G. Wilson and the staff of the McGill Physical Testing Laboratory for their help in developing the laboratory technique.

L. A. Gottheil who was so generous with his time and knowledge.

Miron et Freres Ltee for supplying the coarse aggregate free of charge.

Canada Cement Company Limited who gratefully supplied the cement without charge.

This thesis was made possible through the Miron Fellowships for Graduate Research. The author held the Miron Fellowship in Concrete Studies for the period 1954 - 55.

APPENDIX "A"

1. Mix Design:

The mix design was based on the report of Committee 613 as published in the Journal of the American Concrete Institute Vol. 51, September 1954.

The requirements of the concrete for the experiment were:

1) 28-day strength of 3750 psi.
2) Slump between 1 and 2 inches.
3) Maximum size of coarse aggregate 3/4".

The following are the steps in mix design procedure for the above concrete.

1. Water cement ratio by weight - .557 or 4.9 gal/c.y.
2. Water content - 30.8 gal/c.y.
3. Cement factor - $\frac{30.8}{4.9} = 6.3$ bags/c.y.
4. The given volume of coarse aggregate per unit volume of concrete when using a sand with F.M. of 2.76 is .61. Therefore the volume of coarse aggregate is .61 x 27 = 16.5 c.f./c.y.
5. The volume of cement, assuming the specific gravity as 3.15, is $\frac{6.3 \times 87.5}{3.15 \times 62.4}$ - 2.81 c.f.
6. The volume of water is $\frac{30.8}{6.24}$ - 4.93 c.f.

7. The volume of coarse aggregate is

$$\frac{.61 \times 27 \times 92.5}{2.65 \times 62.4} = 9.23 \text{ c.f.}$$

8. The entrapped air is 2 percent = 0.54 c.f.

Total:- 17.51 c.f.

9. Therefore the volume of the sand must be

$27.0 - 17.51 = 9.49$ c.f./c.y.

10. The weights of the materials per cubic yard are:-

Sand	9.49 x 2.65 x 62.4	=	1570 lbs/c.y.
Stone	.61 x 27 x 92.5	=	1530 "
Water		=	308 "
Cement		=	552 "
	Total:-		3950 lbs/c.y.

As 4.6 percent of the sand is held on the 3/8" screen this must be corrected for in the batch weights of both the fine and coarse aggregates.

The final figures are, then:-

Sand	1642 lbs/c.y.
Stone 1/4 - 3/4	1458
Water	308
Cement	552
Total	3950 lbs/c.y.

All aggregates were practically moisture free as they were stored in a dry room.