range of air contents from 0 to 7 percent for which it was designed.

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BAILEY TREMPER AND W. L. GOODING, *Closure*—Mr. Klieger's discussion of the aggregate correction factor is a worthwhile contribution to the use of the Washington air meter. The necessity of applying the factor with some aggregates is clearly indicated. The method of determining the correction factor proposed by Mr. Klieger appears to be sufficiently precise for most purposes.

DURABILITY OF PORTLAND CEMENT CONCRETE DETERMINED BY PRIMARY DIRECTIONAL FREEZING AND UNIFORM THAWING

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SYNOPSIS

This report describes a freezing and thawing apparatus and a method of test for freezing 3- by 4- by 16-in. concrete beams primarily from one surface.

An automatic freezing and thawing cabinet similar to a commercial locker plant quick-freeze cabinet was equipped with horizontal freezer plates. Concrete beams were placed directly on the freezer plates and frozen. Thawing of the beams was accomplished by the introduction of steam into a system which continuously circulated air over the beams in the cabinet. The maximum temperature of the air was 70 F. during the thawing cycle, and the minimum plate temperature during the freezing cycle was −30 F.

Time-temperature relations are presented for 3-by 4-by 16-in. concrete beams in direct contact with the plates and also with the beams located at different heights above the plates. The investigation developed a freezing and thawing test in which five cycles of primary directional freezing and uniform thawing were produced each day.

The effect of primary directional freezing on 3- by 4-by 16-in. concrete beams cured for 7 days and also for beams cured for 28 days are shown. Length change, sonic modulus, flexural strength, and compressive strength were determined at five cycle intervals.

The data indicate that the primary directional freezing and uniform thawing is a rapid and severe test and that more uniform results can be obtained by using beams which have been cured for a minimum of 28 days, than by beams which have been cured only 7 days.

This paper covers a portion of an investigation of a method of test for determining the soundness of concrete prisms by primary directional freezing and uniform thawing. Most conventional methods of freezing and thawing tests of concrete specimens follow a procedure in which the change in temperature of the specimen proceeds fairly uniformly from all of the outside surfaces of the specimen toward the center of gravity of the smallest cross-sectional area. This procedure duplicates the direction of the change in temperature of some concrete such as bridge rails, exposed parapets, etc., but does not duplicate the direction of the change in temperature of concrete pavement. Excluding joints, cracks and sides of the concrete pavement, the direction of freezing under normal exposure when the temperature drops is from the top to bottom of the pavement.

In order to duplicate the direction of change in temperature of the concrete pavement with a laboratory specimen, it is necessary to change the temperature of the specimen primarily from one surface. This can be accomplished in a freezing procedure by placing the specimen in contact with the horizontal evaporator plate of a refrigeration system with a film of water between the plate and the specimen. By maintaining a low evaporator plate temperature the specimen can be frozen very rapidly at the contact surface, and freezing will proceed toward the exposed surfaces. If insulation is placed on all exposed faces of a concrete specimen when one of the large faces is in contact with the evaporator plate, the specimen will freeze at the contact surface quite rapidly and freezing will proceed uniformly toward the opposite face. If the specimen is not insulated the primary direction of heat transfer is the same, but in addition a slower rate of heat transfer takes place at the exposed surfaces.

DESCRIPTION OF APPARATUS

The lack of specific data concerning the effect of directional freezing and the need of a rapid method of freezing and thawing concrete specimens in our laboratory, prompted the design and construction of a freezing and thawing cabinet in which directional freezing as well as the conventional method of freezing and thawing could be performed. Figure 1 is a photograph of the freezing and thawing cabinet with the doors closed for regular operation. Figure 2 shows a vertical section through the front of the cabinet, which is insulated with rock wool eight inches in thickness.

The lower chamber, in which the freezing and thawing is accomplished, has inside dimensions of 82-in. width, 65-in. height, and 30-in. depth. Insulated and weather-stripped doors provide access to the front of the chamber. The inside of the chamber and the inside faces of the doors are lined with galvanized iron. The bottom of the chamber is sloped to a drain to provide for removal of water.

A stand in the lower chamber supports seven horizontal 22-in. by 60-in. evaporator plates spaced 8 in. apart with the lowest plate 4 in. from the bottom of the chamber. The stand is located in the chamber leaving a space 7 in. in width at the left end of the chamber and a space 15 in. in width at the right end of the chamber in which the necessary refrigeration controls, fittings and con-

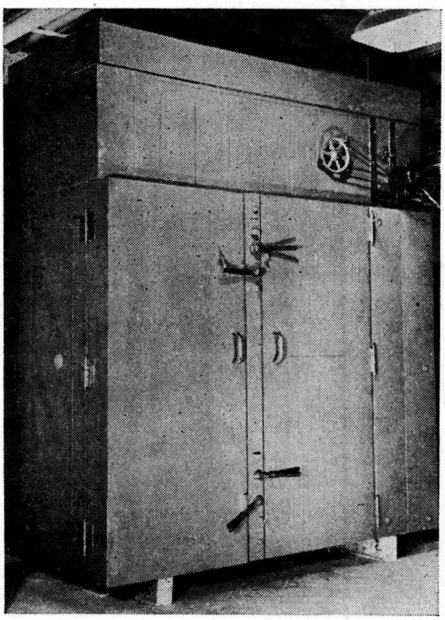

Figure 1. Exterior View of Freezing and Thawing Cabinet

nections are located. Each plate is supplied with refrigerant liquid by means of a Detroit No. 673 (2-ton) expansion valve which allows the plates to be maintained at a minimum temperature of −30 F. The seven overs zed expansion valves are supplied from a manifold in such a manner that a flooded condition of the coils in each plate can be maintained. A more uniform temperature of the evaporator plates is produced when the evaporator plate coils are operated as a flooded system than when the coils are operated as a partially flooded system. The flooded system requires a heat exchanger in the low pressure return line to the compressor.

The upper chamber shown in Figure 2 contains the heating and the air-circulating system and has inside dimensions of 82-in. width, 25-in. height and 26.5-in. depth. A fan enclosure, which is 22 in. wide, 22.5 in. high and 23 in. deep, is mounted over a 7-in. by 23-in. opening through the ceiling of the lower chamber near the right end. An air duct extends from the fan enclosure to another opening of similar dimensions in the left end of the ceiling of the lower chamber. A 10-in. squirrel cage blower fan is mounted in the fan enclosure and is connected to a motor mounted on the outside of the cabinet by means of a belt and pulley system which allows the fan to be driven at approximately 545 rpm. The direction of air flow in the cabinet is counter-clockwise and the quantity of air-flow over the evaporator plates is regulated by vertical baffle plates with adjustable louvers which are located at each end of the evaporator plate stand. The louvers are adjusted so that the same air velocity is maintained at a height of 3.25 in. above the plates.

Electrical switches are provided for automatic and manual control of all elements in the system. A time clock control automatically changes the system from the freezing to the thawing cycle and from the thawing to the freezing cycle. Thermostatic control of the solenoid in the refrigerant line is provided; however, in all of the tests performed to date this control has not been used, and the solenoid is actuated by the time switch.

A compressor having a five-ton refrigeration capacity is run continuously during the freezing cycle, and the minimum temperature produced in the concrete beams is regulated by the length of the freezing cycle. The refrigerant is pumped from the coils in the evaporator plates at the end of each freezing cycle.

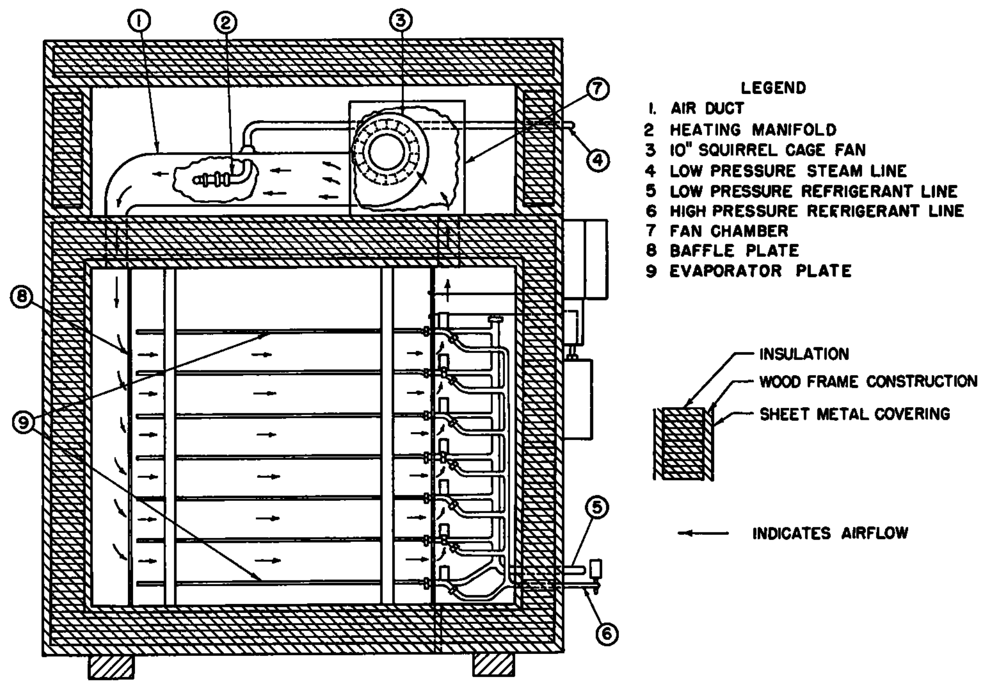

Figure 2. Vertical Section through Front of Cabinet

During the thawing cycle the air from the fan is heated by low-pressure steam (20 to 30 lb.) that is supplied to a horizontal manifold, located in the air duct about 20 in. from the fan. A thermostat actuates a solenoid in the steam line and is set to maintain an air temperature of 70 F. Occasionally a maximum air temperature of 80 F. occurs during a thawing cycle. The fan is operated continuously during the freezing and thawing cycles.

The temperatures of the air and of reference beams located on the plates in the cabinet are determined and recorded by means of thermocouples connected to an eight-point recorder.

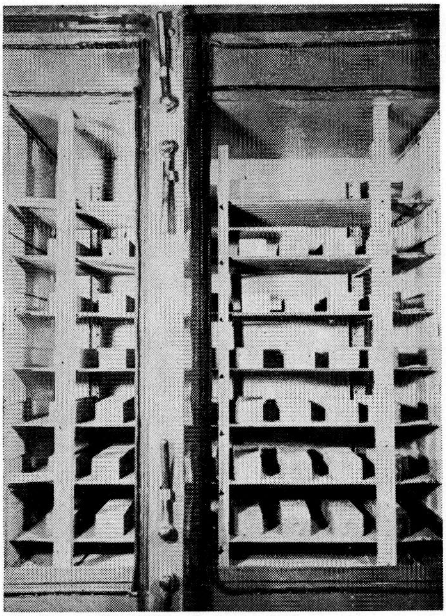

Figure 3. Interior of Refrigeration Cabinet with Beams in Direct Contact with Evaporator Plates

FREEZING AND THAWING PROCEDURES

Figure 3 shows the interior of the cabinet with beams in position on the evaporator plates. Eight concrete beams were placed on each of the six lower plates, and the same load was used for each cycle and for each test. Beams were placed only on the six lower plates in order to attain similar freezing and thawing conditions. The position of the beams on the plates was changed daily and an attempt was made to rotate the beams from one plate to another during the entire test.

When the directional freezing test was performed the six evaporator plates were flooded with water immediately prior to placing the beams on the plates. This was done once each day preceding the first cycle for the day. During each thawing cycle the beams are wet by condensation of steam from the circulating air.

When the conventional method of freezing was followed the beams rested on wood strips or hollow glass cylinders which allowed air to circulate between the beams and the evaporator plates.

INVESTIGATION OF TIME-TEMPERATURE CHARACTERISTICS

The first part of this investigation was made to obtain time-temperature data by freezing 3-by 4-by 16-in. concrete beams by the conventional method and also by primary directional freezing. In order to simplify procedures, the beams were not insulated but were exposed to the surrounding air.

Numerous preliminary freezing and thawing tests were performed to determine characteristics of the apparatus, temperatures of beams and temperature recorder performance. Various periods of freezing and of thawing were tried and a compromise time schedule devised for further investigation. The time clock switches on the freezing and thawing apparatus were set to produce five cycles of freezing and thawing each 24 hours. Table 1 shows the starting temperature, time of freezing and time of thawing for each of the five cycles. The time allowed for thawing in the fifth cycle was three hours and thirty minutes which allowed the beams to remain at 70 F. for two hours before test. One hour was required each day for length measurements to determine the beams that qualified for further treatment. Due to unforseen delays caused by equipment breakdowns and shutdowns over the week-end it was impossible to adhere strictly to the schedule.

A number of trial freezing and thawing tests were performed in order to obtain data to show the variations in temperature of beams in different locations on the plates and also time-

TABLE 1
TIME SCHEDULE OF TYPICAL FREEZING AND THAWING TEST

Cycle No.	Starting Temp.	Time of Freezing	Time of Thawing
	deg. F.	*hr. min.*	*hr. min.*
1	70	3:30	1:15
2	60	2:45	1:15
3	60	2:45	1:15
4	60	2:45	1:15
5	60	2:45	3:30
Total Time		14:30	8:30

temperature data for beams located at different heights above some of the plates. Figures 4 to 8 inclusive show some of the time-temperature records obtained for six beams during the first cycle of freezing and thawing for the day These curves also indicate the possibilities of other types of freezing and thawing cycles.

Figure 4 shows time-temperature records of a trial freezing and thawing test in which all the beams in the cabinet were located $1\frac{3}{4}$ in. above the evaporator plates. One beam contained three thermocouples; one of which was embedded $\frac{3}{4}$ in. below the top of the beam, a second $1\frac{1}{2}$ in. below the top of the beam and a third $\frac{3}{4}$ in. above the bottom of the beam. This beam will be referred to as the three-thermocouple beam. Five other beams each contained a thermocouple located at the center of gravity of the beam. The beams containing thermocouples were located at the right end of the freezing cabinet $1\frac{3}{4}$ in. above different plates. Their placement position is shown at the lower right hand corner of this figure. The 42 other beams included as load occupy the remaining positions in the freezing cabinet but are not shown in the placement pattern. Note that a significant difference in temperature cannot be detected in the top, middle and bottom thermocouple positions in this test. The conditions of freezing and thawing of the beams in the cabinet were such that the beams were frozen and thawed uniformly from the exposed surfaces toward the center of gravity of the beams. This is the type of freezing and thawing generally employed in uniform freezing and thawing tests.

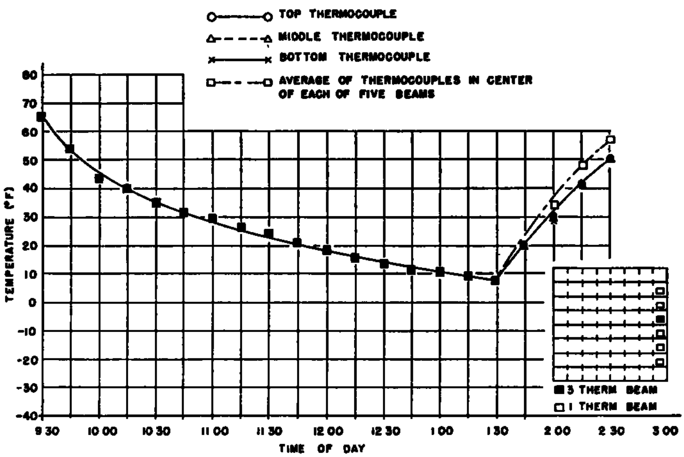

Figure 4. Time-Temperature Record in Trial Freezing and Thawing Test with all Beams $1\frac{3}{4}$ in. above Evaporator Plates.

Figure 5 shows time-temperature records of a trial freezing and thawing test in which all the beams were placed directly on the evaporator plates. The three-thermocouple beam was located at the right end of the cabinet on the lower plate. The single-thermocouple beams were located in the third position from the left end on the remaining plates. The temperature curves are well defined near the middle of the freezing cycle, and the position of the curves corresponds to the position of the thermocouples in the beam. During the period of freezing of the water in the beam, the difference in time of freezing of the bottom and top of the beam is over 15 minutes.

Figure 6 shows the temperatures of the centers of individual beams located on six different plates during one freezing and thawing cycle. If the temperatures of the beams are the same at the beginning of each freezing cycle, the temperatures of the beams will also be very nearly the same at any time during the freezing cycle irrespective of the location of the beams in the cabinet.

Figure 7 shows time-temperature records of another trial freezing and thawing test. The beam containing the three thermocouples was located in the right end of the cabinet, $1\frac{3}{4}$ in. above the lower plate. Only a small differ-

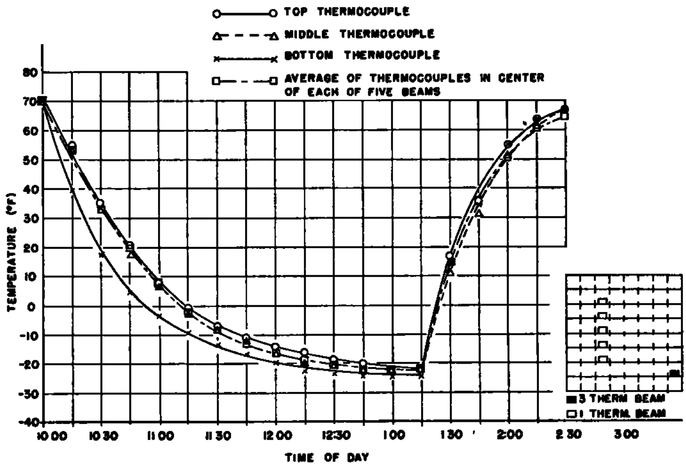

Figure 5. Time-Temperature Record in Trial Freezing and Thawing Test with all Beams in Direct Contact with Evaporator Plates.

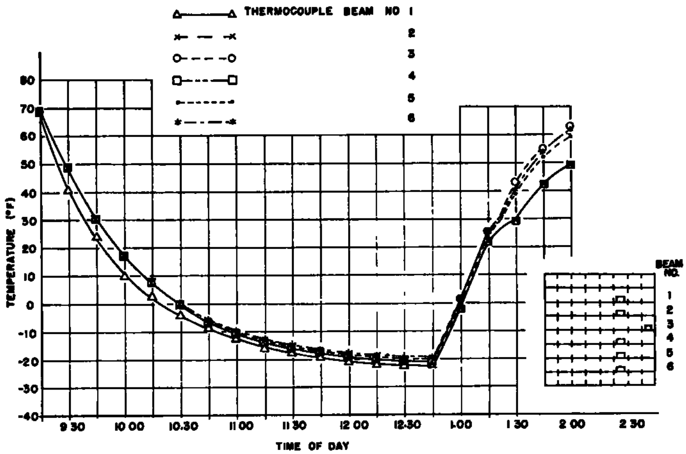

Figure 6. Time-Temperature Record in Trial Freezing and Thawing Test for Individual Beams in Direct Contact with Evaporator Plates.

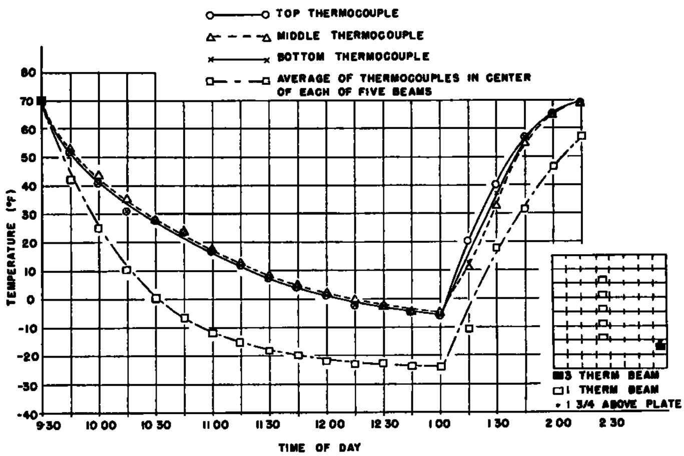

Figure 7. Time-Temperature Record in Trial Freezing and Thawing Test for a Beam $1\frac{3}{4}$ in. above an Evaporator Plate and the Remaining Beams in Direct Contact with Plates.

ence in temperature is shown from top to bottom of the beam containing the three thermocouples. This is indicated by the closely spaced three upper curves. The five single-thermocouple beams were placed directly on the plates in the fourth position from the left end of the cabinet. Their average temperature is shown by the lower curve. At the end of the freezing period there is 18 F. difference in temperature between the beams which are located directly in contact with the plate and the beam located 1¾ in. above the plate.

Figure 8 shows curves for a test similar to those in Figure 7 except that the three-thermocouple beam was located ¼ in. above the plate. The upper curves represent the temperatures in the three-thermocouple beam and the lower curve the average temperature of five beams on the plates. The relative position of the upper curves in Figures 7 and 8 disclose that the temperatures of the beam located ¼ in. above the plate are nearly identical with the temperatures of the beam located 1¾ in. above the plate.

The time-temperature data obtained in the trial freezing and thawing tests indicate that a fast freezing and thawing cycle can be designed with a freezing cycle from 1½ to 3 hours and a thawing cycle from 1¼ to 1¾ hours if the beams are placed directly in contact with the evaporator plates. This method of freezing is similar to the method of freezing which occurs on many highway pavements, although the rate of freezing and thawing may be abnormally accelerated.

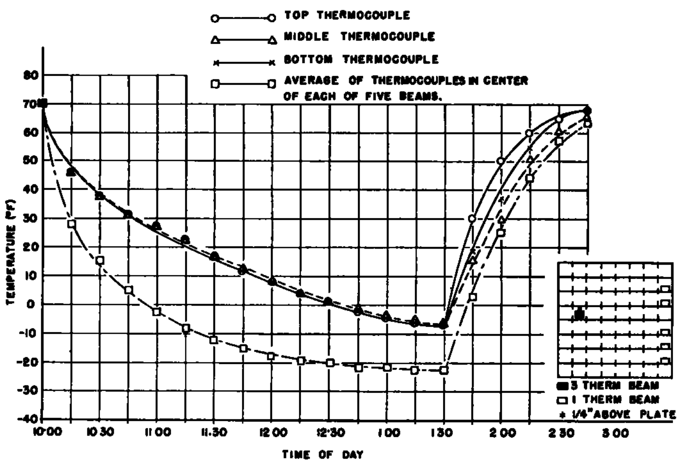

Figure 8. Time-Temperature Record in Trial Freezing and Thawing Test for a Beam ¼ in. above an Evaporator Plate and the Remaining Beams in Direct Contact with Plates.

EFFECT OF DIRECTIONAL FREEZING ON CONCRETE BEAMS

The second phase of the investigation deals with the effect of directional freezing on concrete beams. Ninety-six 3- by 4- by 16-in. concrete beams were fabricated from four concrete mixtures and subjected to the directional freezing and uniform thawing test.

The materials in this investigation were obtained while making another investigation of materials used in the construction of a concrete pavement project. Large samples of each of two type I cements from different mills were taken on the project and were stored in air-tight containers. The physical and chemical analyses of the cements are shown in Table 2. In the cements there were some physical and chemical differences which were significant. Cement No. 2 was slightly finer and contained more tricalcium aluminate than cement No. 1, and as indicated by the physical tests, the mortar which contained cement No. 2 had slightly higher strengths especially at early ages than the mortar which contained cement No. 1.

The fine aggregate was Platte River sand-gravel produced at a commercial pit near Fremont, Nebraska. The coarse aggregate was limestone from a commercial pit near

Earlham, Iowa. The aggregates for each mix were re-graded separately in the laboratory in order to have a more uniform gradation of the combined materials. The gradations of the aggregates are shown in Table 3.

The coarse aggregate was immersed in water for 24 hours prior to use in the concrete mixtures to prevent absorption of the mixing water. Since the fine aggregate had an absorption of about 0.5 percent, it was used in an air-dry condition. In order to compare the data from the freezing and thawing tests with the service behavior of the concrete pavement, the proportions of the materials duplicated the proportions used on the pavement project. The combined aggregate in all of the mixes was composed of approximately 70 percent sand-gravel and 30 percent crushed limestone.

The concrete was mixed in an open-tub type Lancaster mixer, having a capacity of 1¾ cu. ft. All materials were weighed to an accuracy of 0.1 lb. The materials were placed in the mixer in three layers; first, one half of the aggregates, then the cement, and finally the remainder of the aggregates. The materials were dry mixed for one minute and wet mixed for two minutes. The mixing water was added during the first fifteen seconds of the wet mixing period. Immediately after the mixing was completed, the slump, flow, and yield tests were performed on the fresh concrete. After completion of these tests the concrete was returned to the mixer and remixed for ten seconds before fabricating the beams.

Four concrete mixtures were prepared in this part of the investigation. Two of the concrete mixtures identified as 1-A and 1-B were similar mixes and contained cement

TABLE 2
ANALYSIS OF CEMENTS

Identification Data		
Cement No.	1	2
Laboratory Identification No.	C47-209R	C47-208R
Type of Cement	I	I
Physical Tests		
Air Voids in Mortar	5.1	3.4
Normal Consistency	25.0	25.5
Fineness:		
Percent retained on No. 200 sieve	1.4	2.3
Specific Surface, sq. cm. per gm.	1661	1826
Soundness:		
Steam Chest	OK	OK
Autoclave Expansion, percent	0.115	0.101
Time of Setting (Gillmore Test):		
Initial Set, Hr. Min.	3:15	2:00
Final Set, Hr. Min.	5:05	4:40
Tensile Strength, psi.:		
1 Day in moist air, 2 days in water	293	407
1 Day in moist air, 6 days in water	377	450
1 Day in moist air, 27 days in water.	503	497
Compressive Strength, psi.:		
1 Day in moist air, 6 days in water	2542	3183
1 Day in moist air, 27 days in water	3717	4417
Chemical Tests		
Silicon Dioxide (SiO_2), percent	21.5	22.3
Aluminum Oxide (Al_2O_3), percent	5.2	6.6
Ferric Oxide (Fe_2O_3), percent	2.5	3.3
Calcium Oxide (CaO), percent	64.4	65.1
Magnesium Oxide (MgO), percent	3.8	1.0
Sulfur Trioxide (SO_3), percent	1.9	1.9
Loss on ignition, percent	1.3	0.7
Insoluble residue, percent	0.5	0.5
Ratio of Al_2O_3 to Fe_2O_3	2.0	2.0
Tricalcium Silicate ($3CaO \cdot SiO_2$), percent	54.8	40.5
Dicalcium Silicate ($2CaO \cdot SiO_2$), percent.	20.4	33.6
Tricalcium Aluminate ($3CaO \cdot Al_2O_3$), percent	9.5	12.0
Sodium Oxide (Na_2O), percent	0.23	0.24
Potassium Oxide (K_2O), percent	0.55	0.42
Total alkali ($Na_2O + K_2O$), percent	0.78	0.66
Equivalent alkali [$Na_2O + (0.658 \times K_2O)$], percent	0.59	0.52
Water-soluble alkali, percent	0.32	0.05
Phosphorus Pentoxide (P_2O_5), percent	0.10	0.16
Manganic Oxide (Mn_2O_3), percent.	0.07	0.16
Chloroform-soluble organic substances, percent	0.005	0.004
Free Lime (CaO), percent	0.7	0.7

No. 1. The other two mixes identified as 2-A and 2-B were similar mixes and contained cement No. 2. The mix data for the concrete mixes are shown in Table 4. Slightly more water was used in the concrete containing cement No. 2 than in the concrete containing cement No. 1. Mixes No. 1-A and 2-A had more air voids in the fresh concrete than mixes 1-B and 2-B.

TABLE 3
CHARACTERISTICS OF AGGREGATES
Fine Aggregate, Fremont Sand Gravel—Coarse Aggregate, Earlham Rock

Mix No.	Fine Aggregate				Coarse Aggregate				Combined Aggregate			
	1-A	1-B	2-A	2-B	1-A	1-B	2-A	2-B	1-A	1-B	2-A	2-B
Sieve Analysis												
Total percent passing												
¾ in.	100	100	99	100	91	90	90	90	97	97	96	97
½ in.	99	99	97	98	61	63	64	63	87	88	86	87
⅜ in.	97	96	96	97	31	32	33	32	77	77	75	76
No. 4	83	84	83	84	6	5	4	5	60	60	57	58
No. 10	55	54	54	54	4	3	3	3	40	39	37	37
No. 20	31	32	33	32	3	3	3	3	23	23	23	22
No. 30	24	24	26	24	3	3	3	3	18	18	18	17
No. 50	11	11	12	12	3	3	3	3	9	9	9	9
No. 100	2	2	2	2	3	3	3	3	2	2	2	2
Percent of material in combined aggregate	70	70	67	67	30	30	33	33				
Wt. per cu. ft. lb.	118.4	120.9	119.0	119.4								
Percent Voids	27.4	26.2	27.4	27.2								
Specific Gravity	2.62				2.57							
Absorption	0.51				3.2							
Freezing and Thawing Soundness test loss ratio					0.93							
Sodium Sulphate Soundness loss ratio					0.74							

TABLE 4
MIX DATA

Mix Number	1-A	1-B	2-A	2-B
Mix by weight[a]	1:3.83:1.64	1:3.84:1.64	1:3.64:1.78	1:3.64:1.78
Sacks cement per cu. yd.	6.03	6.08	6.07	6.10
Gal Water per sk. of Cem..	5.10	5.40	5.46	5.46
W/C Ratio by weight	0.452	0.479	0.484	0.484
Slump (inches)	2⅞	1⅜	1⅞	2⅜
Flow (percent)	65	50	55	45
Weight per cu. ft. of fresh concrete	145.3	147.0	145.9	146.5
Percent air voids	3.3	1.7	2.2	1.8

[a] Based on saturated surface dry aggregate.

The concrete beams were molded in steel molds of 3- by 4- by 16-in. nominal inside dimensions. The end plates of each of the molds were equipped with a circular removable brass insert that held a ¼- by 11/16-in. stainless steel reference plug in place while the mold was being filled. The molds were filled with fresh concrete at a temperature of 65 to 75 F. in two layers of equal depth. Each layer was tamped ten times along each side and five times at each end of the mold with the finger tips. The surface of each layer was also tamped ten times with the knuckles. After tamping was completed on the second layer, the sides were spaded with a small trowel, and the top surfaces of the beams were floated smooth with a wooden trowel. Twenty-four 3- by 4- by 16-in. beams were fabricated from each of the mixes.

Because the length of cure and the type of cure are factors in the durability of concrete, 48 of the beams were cured by one method and the other 48 were cured by another method. The type and length of cure of the beams are shown in Table 5. All the beams were cured for one day in the molds in a moist closet. The beams were then removed from the molds and returned to the moist closet for six more days of cure. After the moist closet cure, the beams fabricated from mixes 1-A and 2-A were stored in the laboratory at room temperature (65 to 80 F.) for a period of 21 days. Upon completion of the storage in air the beams were immersed in water at 70 F. for a period of two days. The beams fabricated from mix 1-B were immersed in water for two days, after the moist closet cure and those from mix 2-B were immersed in water for four days. The beams from mix 2-B were cured the two extra days in water in order that the freezing and thawing tests could be started immediately after the week-end recess.

Four of the beams from mixes 1-A and 2-A and three beams from mixes 1-B and 2-B were tested for strength at the end of the curing period. The remaining beams from each mix were weighed in air and in water, measured for length, and the sonic modulus of elasticity determined. The beams were then placed in the directional freezing and uniform thawing test.

TABLE 5
METHOD OF CURE

Mix Number	1-A	1-B	2-A	2-B
Days in Moist Room	7	7	7	7
Days in Dry Rack	21	0	21	0
Days in Water	2	2	2	4

A schedule was planned that would provide a similar series of strength tests for each group of beams throughout the freezing and thawing tests that would not disrupt the uniformity of other tests of the beams. After each five cycles of freezing and thawing, three beams from each of the mixes 1-B and 2-B that had the maximum change in length and four beams from each of the mixes 1-A and 2-A that had the maximum change in length were removed from the freezing and thawing test, and tested for strength. The sonic modulus of elasticity and the flexural and compressive strengths were determined on these beams after they were immersed in water at 70 to 80 F. for six hours. This procedure was followed until all beams were tested.

The time clock switches on the freezing and thawing apparatus were set to produce five cycles of freezing and thawing each 24 hours as was shown in Table 1. Unforseen delays caused by equipment breakdowns and shutdowns over the week-end holidays, however, made it impossible to adhere strictly to this schedule. Table 6 shows the starting temperature, the time of freezing and the time of thawing for each cycle. The time that elapsed between the last thawing cycle and the measurements of the beams, and the time that the equipment was shut off, are also included in this table.

The effect of the freezing and thawing test on the 3- by 4- by 16-in. beams is shown in Figures 9 and 10. These figures show the percent change in length, percent loss in sonic modulus, percent loss in flexural strength and the percent loss in compressive strength plotted against the number of cycles of freezing and thawing. These percentages are based on the tests performed on the beams at the end of their respective curing periods.

It should be recalled that the beams which had the greatest change in length were removed first from the freezing and thawing test, leaving the better beams in the test. This is probably the reason that in Figures 9 and 10 the curves, which represent the beams cured for the shorter period, tend to become concave downward near the end of the test.

That part of Figure 9 showing percent change in length plotted against the number of cycles for the short period of curing, shows some variation in the concrete beams in which the different cements were used. A part of this variation may be due to the additional two days immersion in water which mix 2-B received prior to the freezing and thawing test. An insignificant difference between the two cements is shown for concrete beams which were cured seven days in the moist room, twenty-one days in the dry rack and immersed in water for two days. The difference in resistance to freezing and thawing between the beams cured by the two different procedures is very marked.

The curves shown in Figure 11 are based on the same change in length test values as those shown in Figure 9 for mix 2-B and mix 2-A and show the percent change in length plotted against the number of cycles of freezing and thawing. This figure is presented to emphasize the method of selecting beams for removal from the freezing and thawing test and also to show the variations of maximum and minimum values of changes in length. Three curves are shown. Curve A shows the maximum, curve B the average and curve C

TABLE 6

STARTING TEMPERATURES AND FREEZING AND THAWING INTERVALS FOR EACH FREEZING AND THAWING CYCLE

Cycle No.	Starting Temp., Deg. F. for Mixes			Time of Freezing, Hr., Min for Mixes			Time of Thawing, Hr., Min. for Mixes			Time Between End of F. and T and Measurements, Hr., Min. for Mixes			Equipment Shut off after Thawing Cycle Hr., Min. for Mixes		
	1-A and 2-A	1-B	2-B	1-A and 2-A	1-B	2-B	1-A and 2-A	1-B	2-B	1-A and 2-A	1-B	2-B	1-A and 2-A	1-B	2-B
1	65	70	77	3:15	3·10	3:15	1.00	1 45	1:15						
2	69	57	71	2:45	2 00	2:45	1:10	1:15	1:15						
3	65	60	71	2.45	2:45	2:45	1:10	1:10	1:10						
4	66	56	70	2:50	2:45	2 45	1:15	1:15	1:15						
5	65	59	70	2:45	2:45	2:45	3:10	3 00	1.45	6:00	6:00	6:00	1:50	1:15	2:00
6	66	66	70	3:30	3:45	3:15	1:10	1:15	1:10						
7	62	63	67	2:45	2 45	2 45	1:10	1:10	1:10						
8	59	61	67	2:00	2·45	2:45	[a]	1:10	1:10	[a]			25:35[a]		
9	77	54	66	2 45	2 45	2:45	1:10	1:30	1:10						
10	55	63	67	2:45	2.30	2:45	3:00	3:10	2:45	6:00	72:00	6:00	1:30	72:00	1:30
11	69	73	68	3:00	1:10	3:35	1:15	1:10	1:10					24:20[b]	
12	58	72	60	2:45	3:00	2:45	1:10	4:30	1:10						
13	60	71	62	2:45	3:30	2:45	1:10	1:10	1:10						
14	59	66	59	2:45	2:45	2:45	1:10	1:10	1:15						
15	50	68	61	2:45	2.45	2:45	3:15	1:00	3:15	72:00	6:00	6:00	74:30	0:20	2:00
16	56	63	70	2:45	5·00	3·10	1:10	1:10	1:45						
17	53	63	57	2:45	2:45	2:00	1.15	1:10	1:15						
18	53	61	60	2.45	2:45	2:45	1:10	1:10	1:10						
19	52	62	56	2:45	2.45	2.45	1:15	4:30	1:15		6:00			0:55	
20	53	67	59	2·45	3:30	2:45	2:45	1:10	3.00	6:00		6:00	1·30		1:15
21	68	57	66	3:30	2 45	3:45	1:10	1:10	1:15						
22	50	57	63	2:45	2 45	2:45	1:15	1:10	1:10						
23	51	56	61	2:45	2:45	2:45	1:15	1:10	1:10						
24	45	58	54	2:45	2.45	2:45	1:15	3:10	1:30		6.00				
25	51		63	2 45		2:30	3:00		3:10	6:00		72:00			

[a] Blower system failed while on freezing cycle and equipment turned off until repaired. Beams remained in cabinet for 11 hr. 10 min. with unit shut off, then placed in water for 8 hr. and then returned to cabinet Remained in cabinet for 3 hr. before unit was turned on.

[b] Steam line broke. Beams in water for 24 hr.

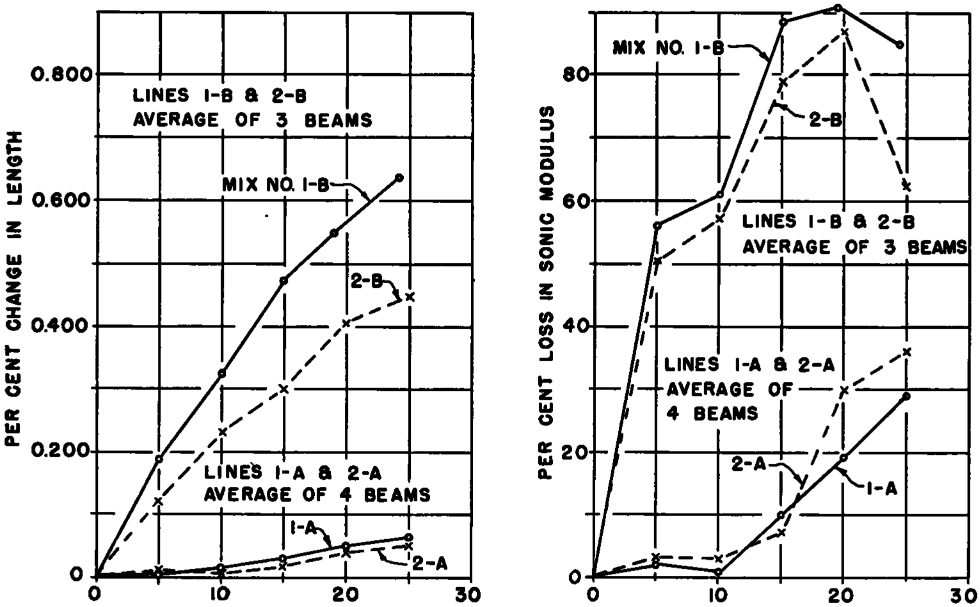

Figure 9. The Effect of Directional Freezing and Uniform Thawing on Length and Sonic Modulus of 3- by 4- by 16-in. Concrete Beams Cured by Two Different Methods.

the minimum value of all the beams tested. For mix 2-B, curve B represents the average of fifteen beams at the end of five cycles, at the end of ten cycles it represents twelve beams and for each succeeding five cycles it represents three beams less. Regardless of whether fifteen beams are tested or whether three beams, the extreme deviation from the average value is about 0.08 percent change in length from mix 2-A were cured seven days in the moist closet, twenty-one days in air and four days in water, and the maximum deviation from the average change of length is 0.03 percent.

Removing the three or four beams which had the greatest change in length simplified the test procedure since the change in length can be determined rapidly and variations in

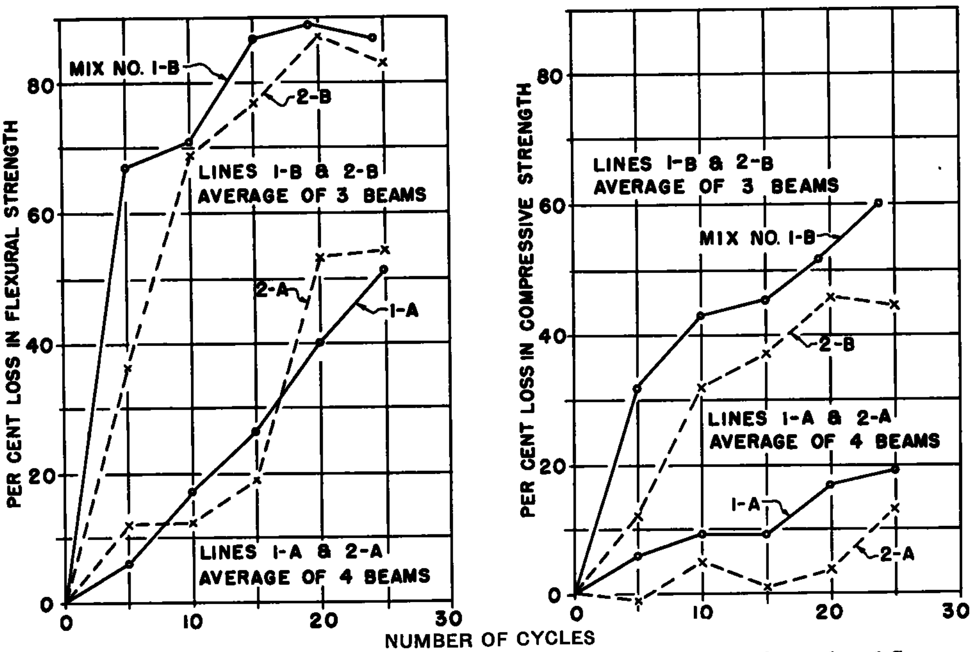

Figure 10. The Effect of Directional Freezing and Uniform Thawing on Flexural and Compressive Strength of 3- by 4- by 16-in. Concrete Beams Cured by Two Different Methods.

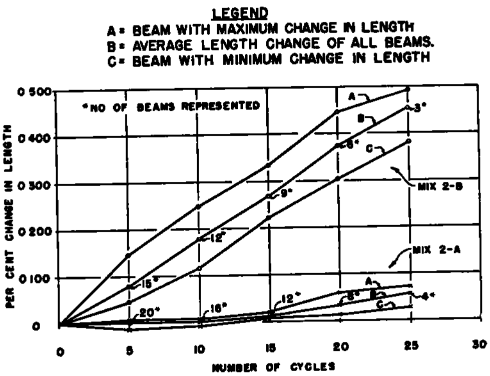

Figure 11. Deviation from the Average Change in Length

for beams which were cured seven days in the moist closet and two days in water. Beams temperature or moisture content during the measurements will have only a slight effect on the change in length.

SUMMARY

This directional freezing and uniform thawing test is a very rapid and severe test. Based on the limited data obtained to date, it appears essential to cure the beams used in this test for at least twenty-eight days. Data has not been presented to show the relation between this method of freezing and the conventional method nor correlation to field performance. These are objects of incomplete investigations. Based on limited data it is estimated that the directional method of freezing produces a degree of disintegration similar to that produced by our conventional method in less than one-tenth the number of cycles.

DISCUSSION

K. B. Woods, *Purdue University*—Mr. Bollen's description of equipment and a method for testing portland cement concrete specimens by primary directional freezing and uniform thawing should stimulate interest in testing and research laboratories. Mr. Bollen's presentation brings to mind some unpublished work done at Purdue University in 1941 in which several portland cement concrete pavement cores were tested by procedures and equipment designed to study frost action in soil.

In the summer of 1939 the State Highway Commission of Indiana constructed some experimental test sections on a section of dual-lane highway on US No. 40 between Knightstown and Dunrieth. Twelve different sections were included in the experiment, which were designed to evaluate the use of various types of cements and additives in preventing surface scaling. In connection with the laboratory program designed to supplement the field observations on this experiment, eight cores were drilled from each of the twelve sections in October, 1940. These specimens were obtained for the purpose of developing the following information[1]: (1) weight per cubic foot of the various sections of concrete; (2) absorption characteristics of the concretes in the various sections; (3) unconfined compressive strength; (4) the relative resistance to freezing and thawing in a ten percent calcium chloride solution; and (5) resistance to directional freezing as determined by equipment used to study frost action in soils.

In connection with the directional freezing, tests were performed on four cores taken from the US 40 project together with four cores obtained from a project from northern Indiana, which had shown susceptibility to scaling. A total of six non-air-entraining cements and two air-entraining cements were included in the eight cores. All eight specimens were saturated by subjecting the cores to one-hour evacuation, plus 23-hr. immersion. The specimens were paraffined on the tops and on the sides to prevent evaporation. They were then placed on a porous disc partially immersed in water in the freezing cabinet.[2] Furthermore, all specimens were insulated on the sides with sand.

Seven slow cycles of freezing and thawing were used, which required approximately twelve weeks of time. The temperature at the top of the specimens was dropped slowly from approximately 30 to −10 F. in about seven-days time. The specimens were then thawed by gradually increasing the temperature. This procedure was repeated until seven cycles were obtained.

The cores were all removed at the end of the seven-cycle test. It was found that all six of the non-air-entraining cement cores had failed and that one of the air-entraining cement cores had also failed.[3] It was concluded in this brief series that concrete with most of the voids filled with water could be destroyed by a slow directional freezing procedure. The study indicates the need for additional research to see whether or not disintegration can be obtained on concrete specimens which have not been previously saturated but which have an available source of water supply.

Guy H. Larson, *Materials Engineer, State Highway Commission of Wisconsin*—Mr. Bollen has presented something quite different from the usual freezing and thawing test. Very desirable features of this test, from the standpoint of economy in time and labor, are the rapid cycle (five per day) and the procedure of freezing and thawing in the same cabinet with the switch from one to the other made automatically. The method simulates field conditions to a certain extent in that the heat transfer is much more rapid from one surface than from the others. Furthermore, the equipment lends itself to the usual types of freezing procedures if desired. A study of the time-temperature curves shows that the rates of freezing and thawing, whether the specimens are above or in contact with the evapora-

[1] Unpublished report on "Concrete Core Study," Joint Highway Research Project, February, 1941, Bound Vol. 13, Vol. III, No. 1, Part A, January 1–March 31, 1941.

[2] "Frost Action in Stabilized Soil Mixtures," by H. F. Winn, Research Assistant, Joint Highway Research Project, Purdue University; *Proceedings*, Highway Research Board, Vol. 18, Part I, 1938, pp. 264–290. (See Figs. 8 & 9.)

[3] Unpublished report on "Concrete Core Study," Joint Highway Research Project, February 1942, Bound Volume 27, Vol. 4, No. 1, Part B, January 1–March 31, 1942.

tor plates, are different in different positions in the cabinet, which indicates a necessity for rotating the specimens.

Apparently the test is quite severe, effecting in 25 cycles a reduction of approximately 30 percent in the sonic modulus with a corresponding reduction of approximately 50 percent in the modulus of rupture of concrete containing 6 bags of cement per cu. yd. and cured 28 days. I am not familiar with the aggregates or heavily sanded mixes used, but with the high cement content the concrete likely is on a par with paving concrete in other sections of the country where more coarsely graded aggregate and a lower cement content are the rule. The relationship between reduction in sonic modulus and reduction in modulus of rupture, checks that obtained in the cooperative test conducted several years ago by the Board's 'Subcommittee on Durability of Concrete—Physical Reactions.'

Referring to Figure 11, the curves show marked differences in all observed properties of the concretes subjected to the different curing conditions. In all probability difference in age of the concrete, as well as difference in curing, was a factor. The curves also show a difference between the two cements, quite marked and consistent when the concrete was tested at the early age, but less marked and less consistent when tested at the later age. Similar concretes usually do show converging test results with increased age.

In some cases the curves indicate that after suffering a large loss in sonic modulus and strength there was a substantial recovery during a succeeding interval in the test, particularly for concrete tested at the early age. This phenomenon probably was brought about by the procedure of selecting for test at a given time the three specimens showing the greatest expansion, and presumably the greatest damage. By so doing, there is a greater possibility of the test results being affected by an accumulation of variables other than those under observation. It would seem better to mold specimens according to a predetermined program and designate certain ones for test at any given future time so as to nullify the effects of such variables as much as possible. Proper distribution in the freezing and thawing cabinet of specimens so designated might greatly reduce the number of rotations necessary to cancel the effect of position in the cabinet. The dispersion of individual test results would likely be increased somewhat, but a smooth curve drawn through the average values would probably present a truer picture of what might be expected of the concrete.

The Wisconsin Highway Commission has done some pilot work on a directional freezing test. The equipment (Fig. A) consists of a cork insulated, metal lined box with inside dimensions approximately 37 by 28 by 23 in., partly filled with saturated sand which is pre-

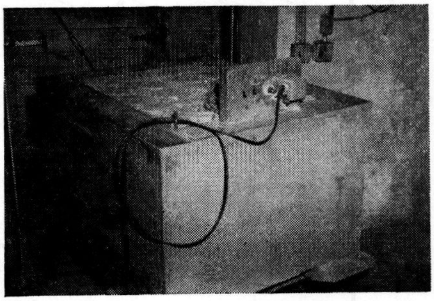

Figure A. Directional Freezing Equipment Loaded with Specimens—Spaces between specimens are filled with insulating material, and upper surfaces only are exposed.

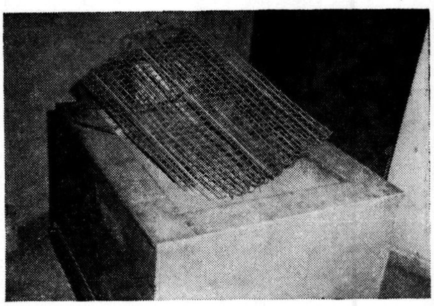

Figure B. The thermostatically controlled heating element is made of soil heating cable, which is placed in the saturated sand and prevents it from freezing.

vented from freezing by means of a thermostatically controlled heating element. The level of the sand is so adjusted that the upper surfaces of the specimens resting on it are flush with the top of the box and exposed to the air. The spaces between specimens are filled with insulating material. The loaded box is mounted on a hand truck and pulled into the freezing room for freezing and removed to the laboratory hallway for thawing. The heating element (Fig. B) consists of a soil heating cable draped in loops and fastened to a piece of expanded metal mesh.

This test is less severe than freezing in air at

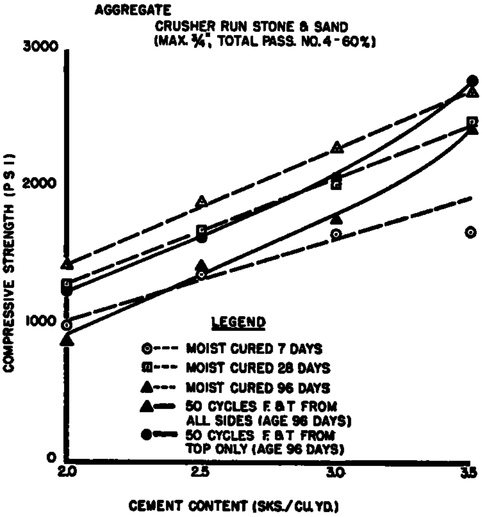

Figure C. The Effects of 50 Cycles of Freezing and Thawing Subsequent to 28 Days of Moist Curing.

−10 F. and thawing in water at 40 F. In a trial test (Fig. C), cylindrical specimens (6 by 5 in.) molded from cement-treated base materials containing 2, 2½ and 3 sacks of cement per cu. yd. of compacted material and cured for 28 days maintained their 28-day compressive strength through 50 cycles of directional freezing and thawing, but were reduced to approximately their 7-day strength in a like number of cycles of freezing in air and thawing in water. Specimens containing 3½ sacks of cement per cu. yd. apparently suffered no retardation in hardening in the directional freezing test, whereas they just maintained their 28-day strength when frozen in air and thawed in water. This method of directional freezing simulates field conditions when a pavement is frozen much more closely than do the conventional tests now used, and perhaps more closely than the procedures described by Mr. Bollen. It has, however, the serious disadvantage of requiring a great deal of time.

The procedure described by Mr. Bollen quickly revealed the differences in durability of concrete resulting from the differences in age and curing conditions employed. If further investigation indicates that it will consistently reveal effects of factors that perhaps are not quite so marked, it may prove to be a big step forward in the development of the freezing and thawing test. Mr. Bollen's paper is a valuable and timely contribution to the data and literature on the subject.