of air maps and the breadth of the band covered by them give the highway engineer full information concerning the character of the neighborhoods being traversed. Air photographs (and mosaics) have proved an invaluable method of making reconnaissance surveys in urban areas within the Chicago region.

(8) "New Role of Aerial Photography," *Civil Engineering*, May 1945; Outlines combination of aerial and ground surveys for post-war highway plans.

PROGRESS REPORT, COMMITTEE ON DURABILITY OF CONCRETE

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SYNOPSIS

A reasonably rapid method for ascertaining the resistance of concrete to freezing and thawing has long been desired by materials testing engineers, but to date such procedures as have been stipulated in specifications have failed to obtain a large following. Since the previous Committee on Durability of Concrete as Affected by the Cement has made some tests in which the effects of different rates of freezing on resistance of mortars to freezing and thawing had been observed, it seemed desirable to study further this important subject.

The program of tests involved: (1) a comparison of the relative severity of a carefully specified coordinating freezing and thawing test as practiced in different laboratories, (2) a comparison of the effects of the freezing and thawing procedures commonly used in these laboratories (local procedures), (3) a comparison of the severity of the coordinating test procedure with the local laboratory procedures.

Tests were made in seven laboratories, and this report describes the testing procedures, discusses the results and arrives at a number of conclusions, among which are: The electronic vibrating devices used provided a convenient and rapid means of determining the change in the dynamic modulus of elasticity of the specimens tested; in these tests the average relation to the percentage decrease in modulus of rupture (R) to the percentage decrease in the dynamic modulus of elasticity (E) due to freezing and thawing was $R = 1.5E$; for the types of concrete tested the relation between the reductions in flexural strength and in dynamic modulus of elasticity was sufficiently reliable to measure the rate of deterioration of the flexural strength under the methods of freezing and thawing used; flexural strength is much more sensitive to the deteriorating effects of freezing and thawing than is the compressive strength; the relation of the reduction in the compressive strength to the reduction in the dynamic modulus of elasticity due to freezing and thawing was so variable in the tests conducted that the reduction in the dynamic modulus could not be used as a measure of the reduction in compressive strength; loss in weight does not provide a criterion of the early deterioration in flexural strength due to freezing and thawing; although there are exceptions, comparison of the load test procedures indicates that in general those procedures in which the rates of freezing from 32° to 15° F. were fast caused failure more quickly than those in which the rates were slow; those local test procedures having fastest rates of freezing and producing quickest failures did not discriminate clearly between the concretes made of satisfactory and those

made of poor coarse aggregate, whereas the procedures in which the rates were somewhat slower and the number of cycles to failure greater provided good discrimination; none of the freezing and thawing procedures tried provided a small dispersion in the number of cycles required for failure and a sufficiently high degree of discrimination to qualify as a standard method.

This committee, an outgrowth of the Project Committee on Durability of Concrete as Affected by the Cement, was formed early in 1940. The object in its formation was to consider and investigate factors related to the durability of concrete. A reasonably rapid method for ascertaining the resistance of concrete to freezing and thawing has long been desired by materials testing engineers, but to date such procedures as have been stipulated in specifications have failed to obtain a large following.

Since the former had made some tests in which the effects of different rates of freezing on resistance of mortars to freezing and thawing had been observed, it seemed desirable to study this important subject further. In arriving at this decision the Committee was well aware that the results of further fundamental research on the causes of deterioration due to freezing and thawing might materially modify such testing procedures as the Committee might now use or prescribe. Nevertheless the Committee felt that the uncertainty of the time at which such fundamental information would be available and the immediate need of a suitable testing procedure were ample justification for the proposed program.

PROGRAM

Essentially the program adopted involved:

(1) a comparison of the relative severity of a carefully specified coordinating freezing and thawing test as practiced in different laboratories.

(2) a comparison of the effects of the freezing and thawing procedures commonly used in these laboratories (local procedures),

(3) a comparison of the severity of the coordinating test procedure with the local laboratory procedures.

Tests providing these comparisons were made in seven laboratories. In six of the laboratories, the tests at each laboratory were run on 120 concrete beams approximately 3 by 4 by 16-in. in size. In one laboratory the beams locally made were 3 by 3 by 11¼ in. in size. Concrete having a water-cement ratio of 0.55, by weight, and a slump of 2 to 3 in. was used in all beams. Half of the beams were fabricated at the Public Roads Administration (PRA) Laboratory under carefully controlled conditions and then shipped to each cooperating laboratory, and half were made in the various cooperating laboratories. Of the beams made in a given laboratory, 30 were made of Potomac River sand and gravel, and 30 were made with local aggregates. Thirty beams made of Potomac River sand and gravel, also 30 beams of Potomac River sand and Bethany Falls, Missouri, limestone of the same water-cement ratio were furnished each participating laboratory by the Public Roads Administration.

Two types of freezing and thawing tests were prescribed, a coordinating test to be standard for all laboratories, and the test usually performed in each cooperating laboratory (local test). Of the 120 beams to be tested by each laboratory, 40 were subjected to the coordinating freezing and thawing test, 40 received the local freezing and thawing test, and 40 were tested after normal moist curing without freezing and thawing. Cement from one bin was furnished by the Portland Cement Association.

Determinations of the absolute volumes required to produce a concrete of 2- to 3-in. slump were made by the Public Roads Administration laboratory. That laboratory advised each cooperating laboratory with regard to specific gravity and absorption values for the different aggregate fractions as well as the cement content of the mix used in Series A, B, and C of Table 1, which gives a schedule of the beams and their allocations.

MATERIALS

The results of the physical and chemical tests made at the different laboratories on the cement used in the program are given in Tables 2 and 3.

The properties of the aggregates used are indicated in Table 4. The sand used in Series

A, B and C was obtained from the Potomac River. Its principal constituents were in approximately the following percentages: quartz 80, quartzite 10, chert 5, sandstone 1.

Gravel (No. 1) for Series A and B was also obtained from the Potomac River. The main constituents were present in the following percentages: quartz and quartzite 72, sandstone 13, chert 12. About 40 per cent of the gravel particles were crushed, the remainder were pebbles.

TABLE 1

Series	Aggregate Designation		Number of 3 by 4 by 16-in. Beams Tested After				Beams Made By
	Fine	Coarse	Coord. Freeze & Thaw	Local Freeze & Thaw	Moist Curing		
					28 Days	Final	
A	Potomac River	1—Potomac River	10[a]	10[a]	5	5	Co-op. Lab.
B	do	1—do	10[a]	10[a]	5	5	PRA
C	do	2—Bethany Falls Limestone	10[a]	10[a]	5	5	PRA
D	Local	Local	10[a]	10[a]	5	5	Co-op. Lab.
Totals			40	40	20	20	

[a] These beams were subjected to tests for change in weight and for dynamic modulus of elasticity after every 5 cycles of freezing and thawing. When the reduction in the dynamic modulus for the pair of beams made on the same day averaged 30 per cent, flexure tests, modified cube tests, and absorption tests were made on them.

TABLE 2
PHYSICAL PROPERTIES OF CEMENT USED IN PROGRAM
(As Determined by the Cooperating Laboratories)

Lab.	Specific Surface (Wagner), cm² per gm.	Time of Set, Gilmore Method hr.-min.		Specific Gravity	Ave. Tensile Strength, lb. per sq. in.			Ave. Compressive Strength, lb. per sq. in.		
		Initial	Final		3 days	7 days	28 days	3 days	7 days	28 days
KSC		2:15	4:00			388	480			
Minn		2:20	4:35			380	428			
MHD	1908	2:40	5:25	3.13		433	500		1,996	3,650
PCA	1925	4:10	6:25	3.17	345	420	525	1,240	2,050	3,220
UW		2:30	5:15	3.17	315	370	435	1,355	2,135	3,720
WHC		2:45	5:20	3.15	295	375	455			

TABLE 3
CHEMICAL ANALYSES OF CEMENT AND COMPUTED POTENTIAL COMPOUND COMPOSITIONS

Laboratory	NBS	KSC	MHD	PCA
Oxide Compositions				
CaO	61.7	61.1	61.6	61.4
SiO_2	20.6	21.0	20.7	20.9
Al_2O_3	5.2	5.4	5.2	5.1
Fe_2O_3	5.0	5.0	4.9	4.8
MgO	3.3	3.6	3.1	3.1
SO_3	1.7	1.7	1.7	1.8
K_2O	1.33	1.30	1.34	1.36
Na_2O	0.03	0.10	0.08	0.05
Ignition Loss	1.3	1.4	1.5	1.4
Ins. Res.	0.09	0.12		0.06
Computed Potential Compounds (Corrected for Free CaO)				
$3CaO \cdot SiO_2(C_3S)$	45.0			41.0
$2CaO \cdot SiO_2(C_2S)$	25.0			29.0
$3CaO \cdot Al_2O_3(C_3A)$	5.0			5.0
$4CaO \cdot Al_2O \cdot Fe_2O_3(C_4AF)$	15.0			15.0
Free CaO	0.65			0.88

The crushed limestone (No. 2) used in Series C was from a formation known locally (in Missouri) as the Bethany Falls. There are two principal members of this formation. These are known as the "massive" and the "nodular." The nodular member grades from a soft, 'shelly' to a much harder and denser formation. In the early period of concrete pavement construction, Bethany Falls limestone containing a considerable percentage of nodular material was accepted as aggregate and its use resulted in some pavements of inferior durability. In each batch, the coarse aggregate for Series C contained 53 per cent of the massive member and 47 per cent of the nodular. This mixture was intended to represent an inferior aggregate which is not acceptable for concrete pavements subjected to freezing and thawing.

PROCEDURE

Preparation of Materials. Coarse aggregate was separated into 3 sizes. For each batch these sizes were recombined approximately as follows: 1 part $\frac{3}{4}$ to 1 in. (square mesh), 2 parts $\frac{3}{8}$ to $\frac{3}{4}$ in. and 1 part No. 4 to $\frac{3}{8}$ in. The sand content was about 40 per cent of the total aggregate, by absolute volume. For exact quantities, see Table 5. All aggregates for the beams of Series A and D were immersed in water for 24 hr. before making beams. The percentage of absorbed water in the aggregate was determined from two representative samples of each aggregate used in each day's mixing program.

TABLE 4
PROPERTIES OF AGGREGATES USED IN PROGRAM
(As Determined by Cooperating Laboratories)

Lab.	Series	Aggregates		Fineness Modulus		Specific Gravity Saturated Surface Dry		Ave. Percentage Moisture[b]	
		Fine	Coarse	Fine	Coarse	Fine	Coarse	Fine	Coarse
NBS	A-27-31	Potomac River	Potomac River			2.60	2.60	1.3	1.1
KSC	A-28-1	" "	" "	2.79	6.92	2.65	2.60		
Minn	A-15-19	" "	" "	2.74	7.26	2.57	2.57	2.4[c]	0.8[c]
MHD	A-28-31	" "	" "	2.65	7.04	2.60	2.60	1.0	1.1
PCA	A-9-13	" "	" "	2.72	6.96	2.60	2.60	1.4	
UW	A-8-13	" "	" "	2.79	7.08	2.61[a]	2.59[a]	1.2	1.0
WHC	A-15-19	" "	" "	2.69	6.98	2.62	2.60	1.2	1.0
PRA	B-Mixes	" "	" "		7.04[d]	2.60	2.60	1.3	1.1
PRA	C-Mixes	" "	Bethany Limestone		7.00	2.60	2.64	1.3	1.9
NBS	D-27-31	" "	Pot. River Kiln Dried			2.60	2.60	1.2	0.8
KSC	D-28-1	Kaw River Local	Lincoln Sandstone Local	2.84	7.26	2.62	2.63		
Minn	D-15-19	Shiely Local	Duluth Trap Local	2.91	7.26	2.63	2.83	1.4[c]	0.4[c]
MHD	D-28-31	Pot. River	Beth. L. S. Local	2.65	6.99	2.60	2.64	1.0	1.9
PCA	D-11-13	Elgin Local	Elgin Local	2.90	7.00	2.65	2.68	1.9	1.7
UW	D-8-13	Janesville Local	Janesville Local	2.84	7.00	2.65	2.67	1.0	1.8
WHC.	D-15-19	Eau Claire Local	Eau Claire Local	2.67	7.03	2.64	2.69	0.7	1.2

[a] Used 2.60 in determining quantities for batches, and above values in calculating absolute volumes in Table 5.
[b] In surface dry aggregates when made into concrete.
[c] As used. Not surface dried.
[d] Average of values determined in A-programs.

A procedure was set up for measuring the required batch weights of saturated coarse aggregates for beams of Series A and D under water and the amounts of saturated surface-wet sand in air. The net amount of water to be added in the mixer was calculated by subtracting the free water held on the surfaces of all aggregate in the batch from the total required to produce a w/c of 0.55, by weight.

Aggregates for beams of Series B and C made at the PRA laboratory were soaked for 24 hr. prior to use. The coarse aggregates were brought to a surface-dry condition and weighed in air. Most of the free water was allowed to drain from the sand after soaking and allowance for the excess remaining on the sand was made daily in determining the amount of mixing water.

Mixing. Machine mixing was used in making beams fabricated both at local laboratories and at the Public Roads Administration laboratory. The following procedure was adopted:

Records of temperature and humidity were kept during making of beams; all materials and apparatus were at room temperature before mixing was begun. Mixing was done at 70° ± 2° F. in all laboratories excepting KSC and PCA which operated at 75° ± 2° F. The average relative humidities in the various mixing rooms were as follows: NBS 49; KSC 60; Minn 52; MHD 62; PCA 45; PRA 50; UW 43; WHC 55 per cent.

The interior of the mixer was moistened by rubbing with a wet rag. Cement, sand and coarse aggregate were mixed dry for 1 min., water was added as specified and mixing was continued for 2 more minutes. The mixer was emptied into a moistened metal pan and the concrete remixed with a shovel for a short period until the batch was homogeneous. The slump was then tested and the concrete placed in molds. No changes were made in proportions of solids or water for batches of

TABLE 5
PROPERTIES OF MIXES

Lab.	Mixer Information			Batch No.	w/c, by wt.	Cem. Cont. sks. per cu. yd.	Slump, in. Range & Average	Sp. Wt. of Concrete at 28 da., lb. per cu. ft.	Absolute Vol. Composition of Concrete in per cent				
	Type	Capacity, cu. ft.	Speed, rpm						Cement C	Sand S	Gravel G	Water W	Air A
NBS	Lancaster LW	0.6	Drum 20 Blade 84	A27-31	0.55	5.45	2.75–6.0 3.7	146.4[a]					
KSC	Lancaster LW	0.6	Drum 18 Blade 78	A28-1	0.55	5.39	2.25–4.0 2.8	147.8[b]	9.5	28.84	43.74	16.64	1.28[b]
Minn	Cylindrical drum 12¼ in. diam. 8 in. high	0.25	Drum 66 Blade 106	A15-19	0.55	5.36	2.5–3.25 2.8	147.7[b]	9.52	29.14	43.34	16.47	1.53[b]
MHD	Lancaster SW	1.6	Drum 17 Blade 72	A28-31	0.55	5.48	2.8–3.3 3.1	149.7[a]	9.7	29.6	44.0	16.7	
PCA	Lancaster LW	0.5	Drum 26 Blade 112	A9-13	0.55	5.35	2.2–3.6 2.8	148.4[b]	9.42	29.6	44.0	16.5	0.53
UW	Tilting converter; 23-in. deep, 21-in. max. diam.; 3 radial blades	1.5	16	A8-13	0.55	5.35	2.4–3.0 2.8	147.5[a]	9.44	29.08	43.59	16.47	1.44
WHC	See UW			A15-19	0.55	5.31	2.2–3.0 2.5	147.5[a] 144.6[b]	9.36 9.24	29.02 28.65	43.53 42.98	16.29 16.08	1.80[a] 3.05[b]
NBS	See above			D27-31	0.55	5.45	2.5–4.5 3.9	146.2[a]	9.67	29.60	44.0	16.75	
KSC	See above			D28-1	0.55	5.39	2.5–3.5 2.8	149.8[b]	9.46	29.36	44.26	16.64	0.28
Minn	See above			D15-19	0.55	5.41	0.72–2.0 1.4	156.4[a]	9.61	29.41	43.73	16.63	0.62
MHD	See above			D28-31	0.55	5.94	3.0–3.8 3.4	150.5[a]	10.4	28.7	42.9	18.0	
PCA	See above			D11-13	0.54	4.09	1.4–3.3 2.3	152.5[b]	7.20	31.2	47.1	12.5	2.00
UW	See above			D8-12	0.55	4.80	2.2–3.4 2.9	149.6[a]	8.46	29.67	44.54	14.77	2.57
WHC	See above			D15-19	0.55	4.63	1.5–2.5 2.1	150.8[a] 147.8[b]	8.14 8.06	29.95 29.63	44.92 44.45	14.16 14.00	2.83[a] 3.86[b]
NBS	Lancaster SW—12 (1934). All B and C specimens made in the P.R.A. laboratory	1¾ cubic feet	11.8 rpm—peripheral speed—92.7 ft. p.m.	B27-31	0.55		3.0						
KSC				B28-31	0.55	5.50	3.0	148.90[a]	9.66	29.45	44.00	16.89	
Minn				B15-19	0.55	5.47	3.0	149.05[a]	9.68	29.40	44.03	16.89	
MHD				B27-31	0.55	5.49	3.0	149.42[a]	9.65	29.45	44.01	16.89	
PCA				B8-12	0.55		3.1						
UW				B8-12	0.55	5.47	3.1	149.32[a]	9.66	29.43	44.03	16.88	
WHC				B15-19	0.55	5.48	3.0	149.1[a]	9.67	29.46	43.99	16.88	
NBS				C27-31	0.55		3.2						
KSC				C28-31	0.55	5.87	3.2	148.9[a]	10.35	28.40	43.19	18.06	
Minn				C15-19	0.55	5.89	3.2	149.94[a]	10.45	28.43	43.01	18.11	
MHD				C27-31	0.55	5.91	3.0	150.42[a]	10.37	28.29	43.30	18.04	
PCA				C8-12	0.55		3.1						
UW				C8-12	0.55	5.90	3.1	150.2[a]	10.42	28.38	43.68	18.12	
WHC				C15-19	0.55	5.89	3.0	149.8[a]	10.40	28.40	43.17	18.03	

[a] From hardened concrete.
[b] From fresh concrete.

materials which had been set by PRA Laboratory.

The types of mixers used in the tests are shown in Figure 1.

Molding. Each specimen was made in two layers each 2 in. deep. Each layer was rodded 17 times with a $\frac{5}{8}$-in. bullet nosed rod. The sides of each layer were spaded 25 strokes and each end of each layer 10 strokes with a 6-in. pointing trowel. Tops were finished with a wooden strike-off. Beams of Series A and D were made six per batch, one batch per day for five consecutive days. Beams of Series B and C (made at PRA Laboratory) were made six per batch on the same days that the corresponding specimens were made by each cooperating laboratory, starting the tests on a given date. Metal molds were used in all laboratories. Joints of molds were made water tight by sealing with Dixon No. 676 graphite grease (Joseph Dixon Crucible Co., Jersey City, N. J.). A thin coat of mineral oil was used on the interior of the molds. Figure 2 shows one type of mold used in the tests.

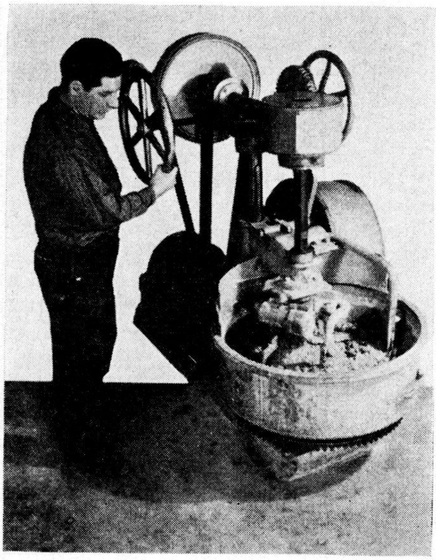

Figure 1(a). Type of Mixer Used by Laboratories, P.R.A., N.B.S., K.S.C., M.H.D., P.C.A.

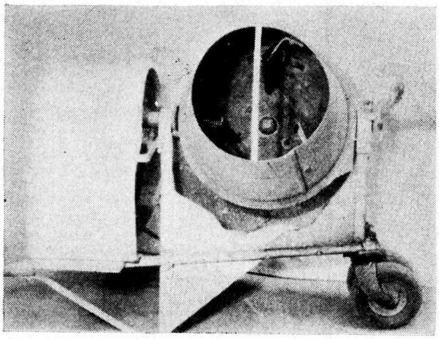

Figure 1(b). Mixer Used by Laboratories U.W. and W.H.C.

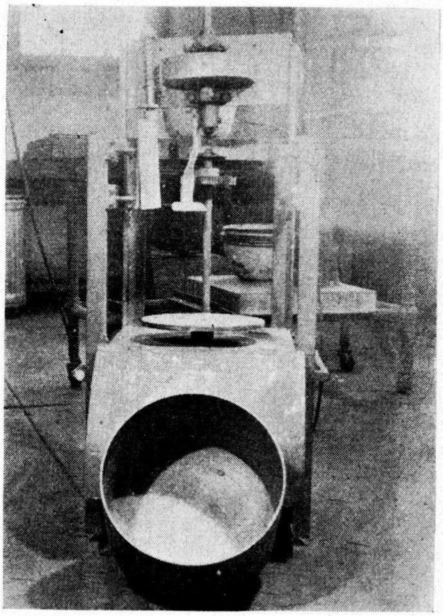

Figure 1(c). Mixer Used by Laboratory Minn.

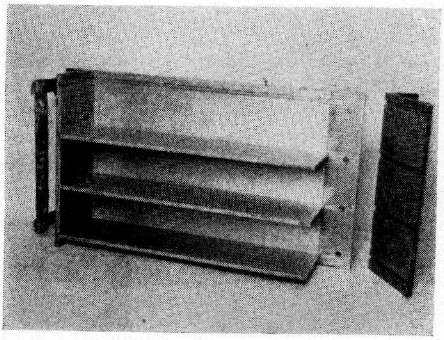

Figure. 2 Mold Used at Laboratories U.W. and W.H.C.

Average properties of all mixes are given in Table 5.

Curing. Immediately after molding, molds and beams for Series A were placed in a moist room at 65° to 75° F. in which exposed surfaces of specimens were kept damp but protected from direct spray of water by sheet metal placed 4 in. above the molds. After one day in the moist room, beams were removed from molds and immersed in water 6 days at room temperature (70° ± 5° F.). They were then cured under damp coniferous sawdust until 21 days old, then immersed in water at 70 ± 5° F. Beams were weighed at the start of the curing period, when removed from forms, immediately after removal from water at 7 days, and immediately after removal from damp sawdust at 21 days.

Beams for Series B and C made at the PRA Laboratory were moist-cured one day, water-cured 6 days at that laboratory, then packed in soaked sawdust in water-tight metal containers and shipped to the appropriate cooperating laboratory. On arrival at the latter laboratory the specimens were held in the containers until 21 days old. Specimens were then weighed to 0.005 lb., placed in water and treated thereafter as indicated in the preceding paragraph.

Beams of Series D were cured the same as those of Series A.

Testing. (1) After 28 days all beams were removed from water and two beams of each batch were subjected to the coordinating freezing and thawing test, described later, and two were subjected to the local freezing and thawing test. The remaining two beams from each batch served as controls. One was broken at 28 days, the other was moist cured until tested at the end of the freezing and thawing program. In testing, loads were imposed at the center of a 4-in. face over a 14-in. span. Loads were applied at such rate that the calculated extreme fiber stress increased at an average rate of 400 psi per min., or less, in loading through the range ½ maximum to maximum load. On a screw-gear driven machine, speeds of head approximated 0.02 to 0.03 in. per min.

(2) Half of each broken beam with its 3-in. faces loaded was subjected to the modified cube compression test (A.S.T.M. C116-39).

(3) Rate of absorption tests were made on all unfractured portions of the half-beams used in the modified cube tests. Specimens were immersed in water at 70° F. for 48 hr. They were then air-dried in a room at 70° F. and 50 to 55 per cent humidity for 21 days and weighed to the nearest gram. Next they were immersed in water at 70° F. and weighed under water at 0, 5, and 30 min., and 5, 24 and 48 hr. after immersion, weighing to 1 gram. The increase of weight in air was found, and the initial weight under water was corrected before the absorptions were calculated.

Coordinating Freezing and Thawing Test. Throughout the test program a constant load was maintained in the freezer using dummy specimens of concrete, brick, or tile, if necessary.

1. After curing for 28 days each beam was surface-dried and weighed to 0.005 lb. It was next tested for dynamic modulus supported first on its 3-in., then on its 4-in. face.

2. Beams to be frozen were then cooled to 40° F. by immersion in water at 40° F. After cooling they were weighed and tested for dynamic modulus of elasticity. The values thus obtained were used in future calculations of losses in modulus.

3. Beams were removed from water and placed top (3-in. face) up on suitable racks in the cold room. It was the aim to reduce temperatures of specimens from 40° F. to 0° F. in not less than 5 hr. and not more than 7 hr. and to make minimum freezer temperatures −10° F. In order to accomplish this end, load-temperature calibrations were run on the freezers. Actual conditions of freezing and thawing are stated in Table 6.

4. In order to obtain the records on rates of freezing and thawing, three or more dummy concrete beams of similar proportions and size each equipped with a resistance thermometer or suitable thermocouple buried in its center were placed in such positions that the range and average temperature of the freezer could be ascertained. The thermometer or thermocouple read to 1° F. and was attached to a suitable device for reading temperatures.

5. After 18 hr. beams and dummies were removed from the freezer and immersed for 6 hr. in water maintained at 40° F. ± 3° F., see Table 6.

6. Beams and dummies were then returned to racks in cold room.

7. After 0, 2, 5 and following every 5 cycles of freezing and thawing, each saturated beam was surface dried with a towel and weighed to 0.005 lb. It was then tested for the dynamic modulus of elasticity supported first on the narrow and then on the broad face. Weight and modulus determinations were made between the 5th and 6th hours of the thawing period keeping the beams at 40° F. during these tests. After weighing and testing for the dynamic modulus, beams were returned to the water bath, kept at 40° F., and finally to the freezer. Cycles were run 5 days per week and specimens remained frozen over the 6th and 7th days.

8. Weight and dynamic modulus tests were run on the control beams in the moist room at 28 days and at approximately 4-week intervals thereafter.

TABLE 6
FREEZING AND THAWING PROCEDURES AND TEMPERATURES

Lab.	Program	Size of Specimen for Series A and D	Specimen Frozen in Air, Water, or Partly Immersed	Temp. of Specimen Entering Freezer deg. F.	Time in Minutes to Lower Specimen Temp. to (deg. F.)					Method of Thawing	Time in Min. to Raise Spec. Temp. to (deg. F.)			Cycles per Day
					32°	25°	15°	0°	−10°		32°	40°	v°	
		in.												
NBS	C	3 x 3½ x 15	Air	(40–45) 42	23	56	127	350		Immersed in water at 40°				1
KSC	C	3 x 4 x 16	Air	40 ± 2	150	215	425*			" "	15	60		1
Minn	C	3 x 4 x 16	Air	40	56		151	255		" "	35	60		1
MHD	C	3½ x 4½ x 16	Air	(38–42) 40	25	60	136	340	463[a]	" "	20	47		1
PCA	C	3 x 3 x 11¼	Air	(40–45) 42	26	62	128	354		" "	29	58		1
UW	C	3 x 4 x 16	Air	(40–46) 42	34	76	135	302	607	" "	17	36		1
WHC	C	3 x 4 x 16	Air	40	33	75	153	352	(−8.5) 720	" "	45	138		1
NBS	L	3 x 3½ x 15	In boots in water; boot immersed in alcohol, water	70	16	23	27	36	46	Boots in 70° tank of water	19	24	(70°) 66	
KSC	L	3 x 4 x 16	Air	35–70	80	125	190*			Thawed in water at 80° 1 hr.	20	25	45	Var.
Minn	L	3 x 4 x 16	In ½-in. water	80	28[c] 71		110[c] 153	208[c] 251	300[c] 343	Immersed 3½ hr. in water 79–81°F.	12	16	(60°) 24	3
MHD	L	3½ x 4½ x 16	Air—10 hr. in cold room, 2 cycles per day	40	24	70	154	468	590[a]	2 hr. in 40° water	24	51		2
PCA	L	3 x 3 x 11¼	In rubber boots in water—Boots in CaCl₂ brine	70° A.M. 55° P.M.	14	29	54	94		Boots thawed in tanks at 80°F. down to 60° F.[e]	48[b]	66[b]		2
UW	L	3 x 4 x 16	In ⅛-in. of water	(60–63)	77[c] 155	194[c] 272	291[c] 369	530[c] 608	745[d] 823	70° air 6 hr. thaw immersed in 60° water 4 hr.	118	185	(60°) 330	1
WHC	L	3 x 4 x 16	⅛ to ¼ in water	63	66	120	177	279	(−8.5) 480	6 hr. in ⅛ to ¼ in. of water in air at 70°	102	162	(63°) 360	1

* Different freezers used in Local and Coordinate programs.
[a]—To −3° F.
[b]—6°F. to temp.
[c]—Time from 40°F.
[d]—To −6° F.
[e]—2 hr. day and 18 hr. at night.

9. When the average dynamic modulus for a pair of beams of a given series A, B, C, or D, subjected to freezing and thawing, dropped 30 per cent below the average initial modulus for the same beams, the beams were allowed to remain immersed in water at 40° F. for 20 hr. after the last dynamic modulus reading.

They were then broken in the saturated condition (excepting half of beams of Series D) on a 14-in. span under center loads applied to their 4-in. faces. The corresponding five moist-cured control beams were also broken and the average modulus of rupture of the frozen and thawed and of the moist cured control beams were calculated and compared.

At the KSC laboratory a half program of five specimens per point was operated. The freezing and thawing tests in that laboratory were discontinued on all five specimens of a type when their average drop in dynamic modulus approximated 30 per cent.

After the dynamic modulus of beams of Series D was reduced 30 per cent, 5 representative specimens were broken. The remaining 5 beams were placed in water at 70° ± 5° F. and tested for dynamic modulus of elasticity after 1, 2, 3, 5, 10, 20 and 30 days. They were then broken in bending while saturated.

10. Compressive tests by the modified cube method with 3-in. faces loaded were made on one half of each beam broken in (9) and compressive strengths of frozen and moist-cured beam portions were compared.

11. Rate of absorption tests were made on the remaining portions of the moist-cured control beams and on the portions of the frozen and thawed air-dried beams.

Local Freezing and Thawing Test Procedures. The methods and temperature characteristics of the local freezing and thawing cycles used in the different laboratories are indicated in Table 6.

DISCUSSION OF RESULTS

Comparison of Frequency Readings at Different Laboratories. An extra set of B and of C beams was made at the PRA Laboratory and held there in moist storage for 784 days, at which time they were sent to the NBS and WHC laboratories for freezing and thawing tests. (See subsequent discussion.) Just before shipment, frequency readings were taken at the PRA laboratory and within a few days readings were again taken at NBS and WHC laboratories. The data of Table 7 show both the uniformity of the readings at the different laboratories and the uniformity of the readings on the different specimens of a group. The average deviations of individual frequencies from the various group means ranged from 0.4 to 1.4 per cent and averaged 0.7 per cent. These data indicate good uniformity in the dynamic modulus values for these beams. The average percentage deviations listed under the NBS and WHC laboratories show the average of the deviations of their readings from those obtained by the PRA laboratory on the same beams. Considering algebraic averages only, the data indicate that the readings at the NBS and WHC laboratories were slightly higher than those obtained at the PRA laboratory by 0.15 and 0.4 per cent, respectively. These data clearly indicate that the electronic vibrating devices used in these experiments are of sufficient accuracy for such tests and show excellent correlation between readings taken at different laboratories.

Range of Reduction in Dynamic Modulus of Specimens. The most disturbing factor in the data is the variation in the number of cycles of freezing and thawing required to produce a reduction of 30 per cent in the dynamic modulus of elasticity of individual specimens tested in a given laboratory. Although the weights of all individual beams and the weights, strengths and dynamic modulus values of the individual control beams, were on the whole remarkably uniform, nevertheless the rates of deterioration found by either local or coordinating test procedures differed widely as is illustrated in the E-N graphs of Figures 3 and 4 for beams of Series B and C tested in the coordinating program.

Despite the dispersion of the E-N graphs for individual specimens, the average E-N graphs of Figure 5 for six of the seven laboratories are in reasonable accord. Hence it is believed that with still closer control of variables the coordinating test program can be developed into a reliable standard procedure.

Relation of Reduction in Flexural Strength to Reduction in Modulus of Elasticity. Since the reduction in the dynamic modulus of elasticity of the concrete specimens was used as a criterion of their loss in flexural strength, which is an important measure of approaching failure, it is decidedly important to examine the relationship between these two mechanical properties in the data of these tests. For the coordinating program of Series A to D, Figure 6 is a plot of the individual reductions in modulus of rupture against the corresponding reductions in dynamic E. On Figures 6 to 13 inclusive are shown Reagel's curve $R = 0.6E^{0.6}$, and a straight line, $R = 1.5E$, connecting the origin with the centroid of the individual points for beams of all laboratories except KSC.

Figure 9 shows the average reductions in modulus of rupture vs. average reductions in dynamic E for each series of the coordinating program. To assist in comparisons both Reagel's curve and the straight line are indicated. Examination of the results from the individual laboratories indicates that the data for MHD and WHC laboratories are somewhat above, and those for the NBS and KSC laboratories are somewhat below the average line.

For the local programs A to D, similar information is presented in Fig. 10 to 13. The average straight line for the local programs is close to that for the coordinating programs ($R = 1.5E$). Scrutiny of the local program results for individual laboratories, Fig. 13, reveals that data from NBS, WHC and UW laboratories lie somewhat above while those of KSC and Minn are considerably below the average line.

The test results confirm the reports from other investigations[1] that the reduction in the dynamic modulus of elasticity affords a satisfactory means of estimating the loss in flexural strength under controlled conditions similar to those existing in these test programs.

TABLE 7

COMPARISONS OF RESONANT FREQUENCY READINGS IN DIFFERENT LABORATORES

Spec. No.	Frequencies at Laboratories in c. p. s.			Spec. No.	Frequencies at Laboratories in c. p. s.		
	PRA	NBS	WHC		PRA	NBS	WHC
B151	1,750		1,770	C151	1,705		1,700
B152	1,750	1,750		C152	1,725	1,730	
B154	1,740	1,755		C154	1,740	1,735	
B155	1,760		1,760	C155	1,730		1,730
B156	1,740	1,740		C156	1,750	1,735	
Ave.	1,748	1,748	1,765	Ave.	1,730	1,733	1,715
[a]Ave. % Dev.	0.37	0.29	0.57	Ave. % Dev.	0.69	0.48	0.15
B161	1,745		1,750	C161	1,740		1,740
B162	1,750	1,755		C162	1,730	1,745	
B165	1,735		1,740	C164	1,735	1,740	
B166	1,725	1,750		C165	1,755		1,760
				C166	1,735	1,745	
Ave.	1,739	1,752	1,745	Ave.	1,739	1,743	1,750
[a]Ave. % Dev.	0.50	0.85	0.29	Ave. % Dev.	0.39	0.57	0.14
B171	1,700		1,710	C171	1,735		1,740
B172	1,720	1,720		C172	1,725	1,740	
B174	1,725	1,750		D174	1,735	1,740	
B175	1,750		1,770	C175	1,655		1,680
B176	1,745	1,755		C176	1,715	1,725	
Ave.	1,728	1,742	1,740	Ave.	1,713	1,735	1,710
[a]Ave. % Dev.	0.90	0.67	0.86	Ave. % Dev.	1.36	0.58	0.87
B181	1,760		1,770	C181	1,740		1,750
B182	1,760	1,765		C182	1,760	1,740	
B183	1,755	1,775		C184	1,755	1,740	
B184	1,730		1,750	C185	1,745		1,730
B185	1,740	1,750		C186	1,740	1,750	
Ave.	1,749	1,763	1,760	Ave.	1,748	1,743	1,740
[a]Ave. % Dev.	0.64	0.66	0.85	Ave. % Dev.	0.44	0.87	0.72
B191	1,740		1,750	C191	1,720		1,730
B192	1,720	1,735		C192	1,730	1,740	
B194	1,750	1,755		C195	1,750		1,750
B195	1,770		1,770	C196	1,760	1,750	
B196	1,735	1,740					
Ave.	1,743	1,743	1,760	Ave.	1,740	1,745	1,740
[a]Ave. % Dev.	0.78	0.48	0.28	Ave. % Dev.	0.86	0.57	0.29

[a] Deviations are based on PRA values.

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[1] See List of References.

Relation of Increase in Flexural Strength of Control Beams to Increase in Dynamic Modulus of Elasticity. A graph of the last two columns of Table 8, in which the average percentage increases in modulus of rupture were plotted against the corresponding average increases in modulus of elasticity, showed a wide scatter in the field of points. The scatter is probably due in part to variations in the coarse aggregates used and differences in the ages of the specimens tested at the end of the freezing and thawing periods. The average of all ratios of percentage increase in modulus of rupture (R′) to percentage increase in dynamic E (E′) is 1.2 to 1.

Influence of Freezing and Thawing on the Compressive Strength. In the following comparisons one should appreciate that the compressive strengths of the 28-day control specimens were quite uniform. The range in the average 28-day strengths for the A specimens as found in the different laboratories was 3680 to 4690; for the B specimens 4074 to 4680; and for the C specimens 4218 to 4620 lb. per sq. in. The grand averages for all laboratories for the A, B, and C 28-day control specimens were 4256, 4274 and 4400 lb. per sq. in., respectively.

A comparison of the data on modulus of rupture and compressive strength for the A, B, and C specimens is provided in Table 10. Only data for test procedures which caused losses in flexural strength due to freezing and thawing are included. On account of the variables in aggregates tested the D-specimens are omitted from this comparison. The comparisons in Table 10 show that the freezing and thawing tests produced more variable and much less potent effects on the compressive strengths of the concretes tested than on the flexural strength. Considering all the data in Table 10 it will be observed that an

TABLE 8
RESULTS OF STRENGTH AND DYNAMIC MODULUS TESTS ON CONTROL BEAMS

Lab.	Series	Modulus of Rupture, lb. per sq. in.					Age Increase After 28 Days, in days	Average Per cent Increase Between 28-days and End of Freezing & Thawing Period, in	
		At 28 days		At End of F. T. Period					
		Ave.	Ave. Dev.	Ave. Age, Days	Ave. Mod. of Rupture	Ave. Dev.		Dynamic E	Mod. of Rupture
			%			%			
NBS	A27-31	702	9.8	126	847	3.4	98	7.6	20.6
KSC	A1-5	703	6.2	72[a]	670[a]	7.8[a]	44	6.0[a]	4.7
Minn	A15-19	663	6.6	589	714	8.7	561	18.5	7.7
MHD	A28-31	841	6.1	56	863	5.7	28	2.0	2.6
PCA	A9-13	704	4.6	58	747	4.9	30	4.0	6.1
UW	A8-13	653	2.5	911	770	5.9	883	19.5	17.9
WHC	A15-19	628	8.6	1,031	742	14.5	1,003	16.4	18.2
NBS	B27-31	695	4.6	264	739	2.8	236	14.4	6.3
KSC	B27-31	662	5.4	108[a]	764[a]	3.8[a]	80	10.4	15.4
Minn	B15-19	656	3.5	72	884	8.8	44	8.9	34.8
MHD	B27-31	798	6.0	78	830	8.0	50	3.3	4.0
PCA	B8-12	662	4.8	200	714	6.9	172	15.4	7.8
UW	B8-12	675	6.7	680	706	4.9	652	20.2	4.6
WHC	B15-19	720	5.0	122	813	4.3	94	12.3	12.9
NBS	C27-31	804	7.4	67	899	7.4	39	6.1	11.8
KSC	C27-31	778	4.4	47	874	2.6	19	4.0	13.1
Minn	C15-19	794	6.7	34	846	2.9	6	2.0	6.6
MHD	C27-31	897	7.5	37	930	7.2	9	1.0	3.7
PCA	C8-12	787	6.6	37	794	8.9	9	2.0	0.9
UW	C8-12	768	7.3	65	832	13.7	37	7.5	8.3
WHC	C15-19	854	4.0	41	928	4.7	13	4.7	8.7
NBS	D27-31	772	2.6	247	875	4.1	219	10.4	13.3
KSC	D1-5	757	8.2	80	768	4.0	52	6.3[a]	1.5
Minn	D15-19	789	6.1	511	1,011	5.4	483	9.8	28.1
MHD	D28-31	981	2.1	35	955	4.5	7	0.7	−2.6
PCA	D11-12	738	6.7	72	903	5.3	44	8.0	22.3
UW	D8-12	598	1.2	711	860	4.6	683	29.6	43.7
WHC	D15-19	544	6.6	1,031	583	12.5	1,003	11.2	7.2
Average of All								9.3	11.5

[a] 3 specimens.

average reduction in dynamic modulus of 30 per cent corresponded to an average decrease in the modulus of rupture of 45 per cent but an average loss in compressive strength of only 9 per cent.

Appearance of Specimens after Freezing and Thawing. Specimens tested in the coordinating program exhibited little or no surface erosion. After prolonged exposure certain specimens containing unsound particles near the surface showed spalling or chipping of the mortar from the surface of such particles. This behavior is apparent in Figure 14a of gravel concrete specimen D9-3 after 380 cycles in the UW coordinating program. That specimen then had an 18 per cent loss in dynamic E and with its companion D9-5 exhibiting a 42 per cent loss in dynamic E was placed in the water-curing recovery program.

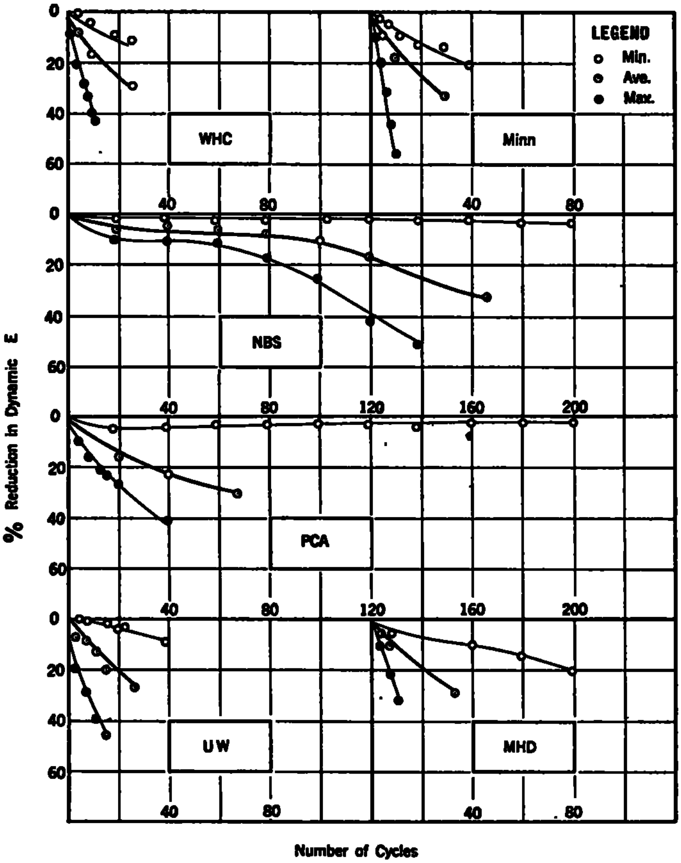

Figure 3. Range in Reduction in Dynamic E vs. Number of Cycles. B Series, Coordinating Program

Specimens in local programs partially immersed in water gave a variety of surface evidences of approaching failure after numerous cycles of freezing and thawing. Frequently, corner spalling, edge spalling, popping of surface mortar over chert or other nondurable particles was observed. These evidences may be seen in Figure 14b showing specimen D10-2 of UW program after 382 cycles when its loss in dynamic E was 40 per cent and its loss in modulus of rupture based on 28-day control average was 31 per cent. Surface disintegration over the immersed portion of beams subjected to such local programs began rather early as shown in Figure 14c for Beam B8-1 of the UW program after 54 cycles at which time its loss in dynamic E was only 2 per cent and its loss in weight was 0.6 per cent. That beam was broken after 304 cycles at which time its losses in E, in modulus of rupture and in weight were 39, 60 and 2.9 per cent respectively.

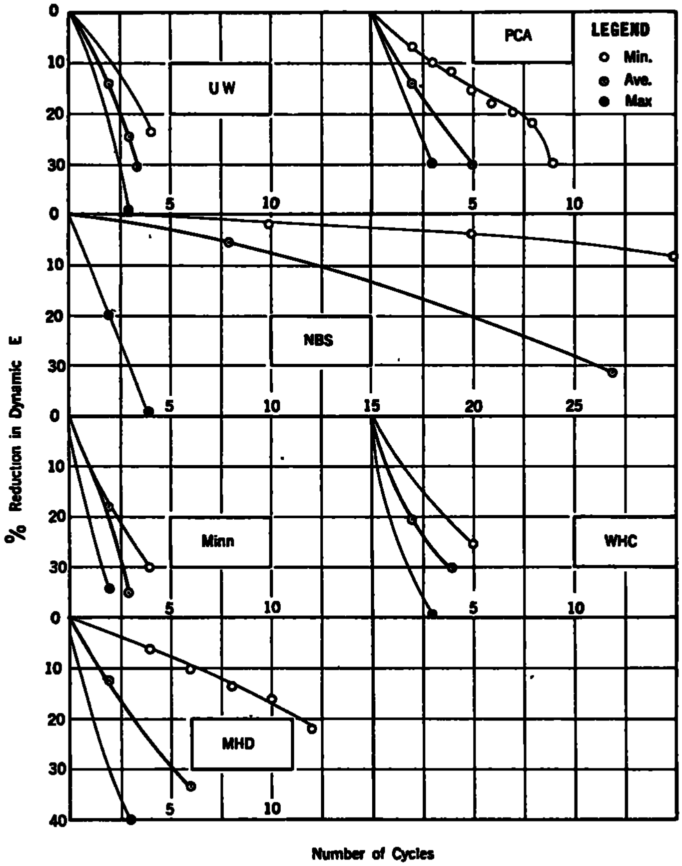

Figure 4. Range in Reduction in Dynamic E vs. Number of Cycles. C Series, Coordinating Program

Evidence of pronounced disintegration of the immersed portions of specimens of the A Series of the WHC local program after 670 cycles are furnished by Figure 14d for Specimens A14, A17, A29, and A26. The percentages of loss in weight for these beams were 4.3, 7.0, 6.3, and 6.0, respectively, average 5.9; and the percentages of loss in dynamic E were 4.9, 19.8, 14.9, and 11.5, respectively, average 12.8.

Uniformity of Coordinating Test Procedure. So far as the data in Table 6 indicate, the rates of cooling the beams from 32° to 15° F. in six of the seven laboratories were reasonably uniform. The average time required for this change to take place varied from 95 to 120 min. The rate of freezing record for KSC laboratory appears to be too slow to be consistent with the number of cycles required to cause failure as indicated in Table 9 for beams of Series B and C in the coordinating program.

Considering the data of Table 9 and Figure 15 for the Series B coordinating program, it should be observed that the strength of the concrete as measured by the 28-day controls was remarkably uniform for each of these series. The high strengths of MHD laboratory beams was doubtless due to the faster speed of loading, 0.05 in. per min., used in breaking those beams. In the freezing and thawing tests on the other hand small changes in moisture or in air content of the concrete and the heterogeneity of aggregate No. 1, with its chert and sandstone pebbles, may have contributed to the variability in the durabilities of the individual beams. The individual beams of aggregate No. 2, although less resistant to freezing and thawing than those of aggregate No. 1, exhibited less variation in resistance to freezing and thawing.

The average percentage reduction in dynamic E for Series B, considering seven laboratories, was 30 per cent, range in laboratory averages 27 to 32. The average reduction in modulus of rupture was 44 per cent, range in averages of 26 to 53 per cent. For the six laboratories performing the full program, the reduction in modulus of rupture averaged 47 per cent and the range in averages was 39 to 53. Why the NBS specimens required 167 cycles to cause failure is not apparent from the available data. The number of cycles required to cause failure in the tests on B beams performed at the other six laboratories varied from 26 to 67 cycles. The dispersions in number of cycles, in reductions in E and moduli of rupture for the different laboratories show that unless closer control of the degree of saturation is obtained more than ten specimens should be tested to secure

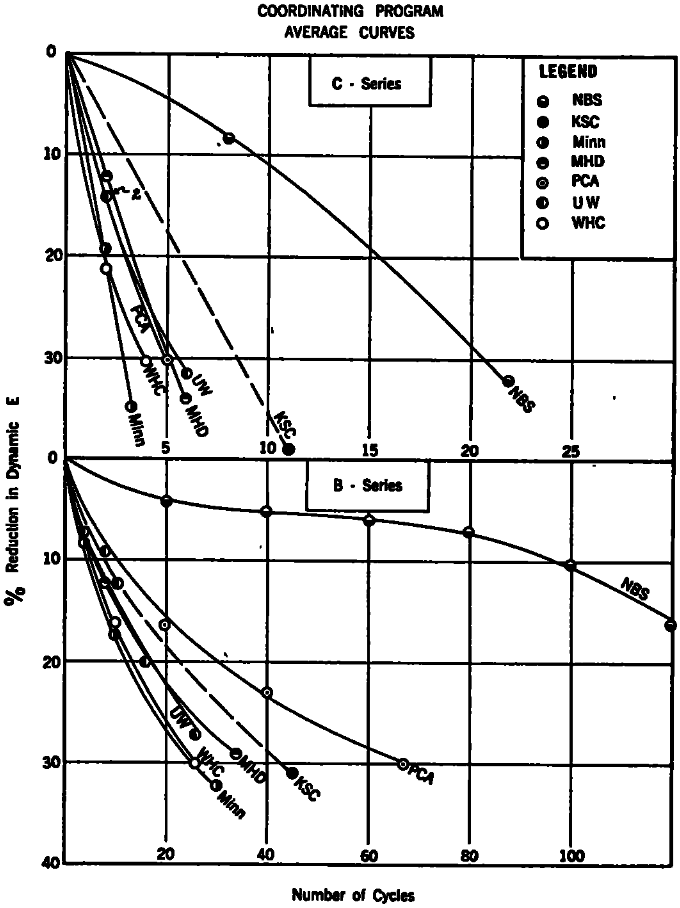

Figure 5. Average Reduction in Dynamic E vs. Number of Cycles. Coordinating Program

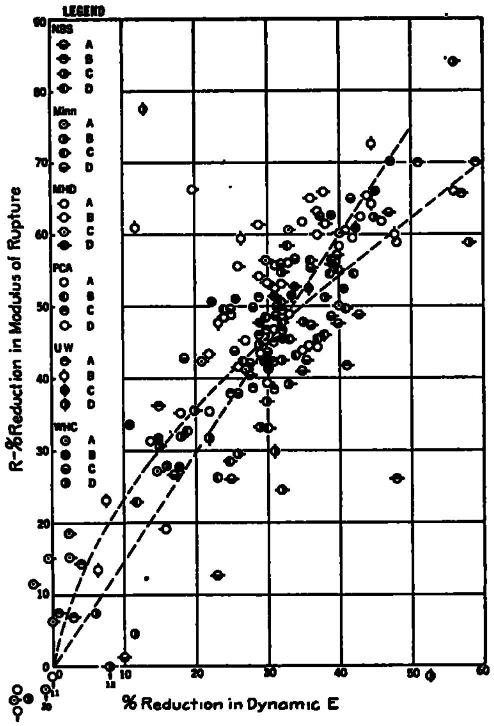

Figure 6. Individual R-E Values for Coordinating Programs

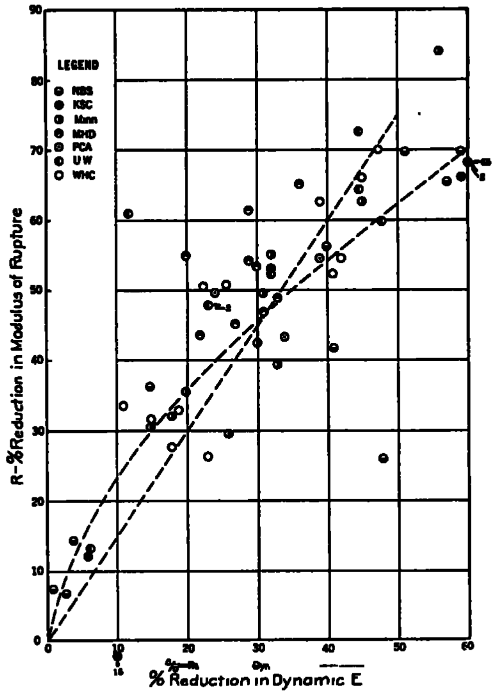

Figure 7. Individual R-E Values for B Series Coordinating Program

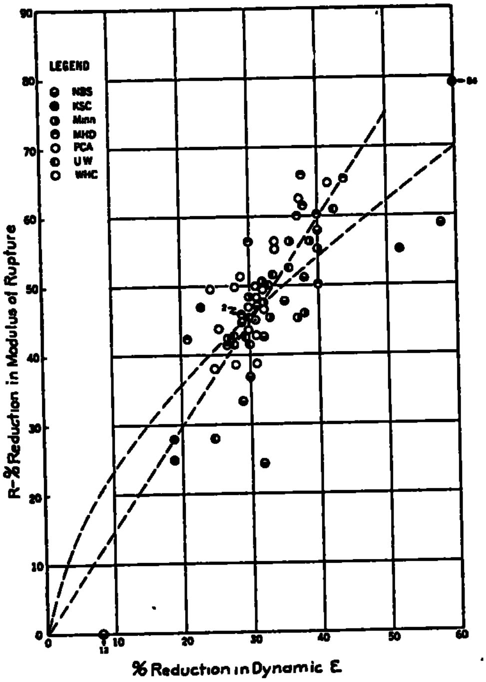

Figure 8. Individual R-E Values for C Series Coordinating Program

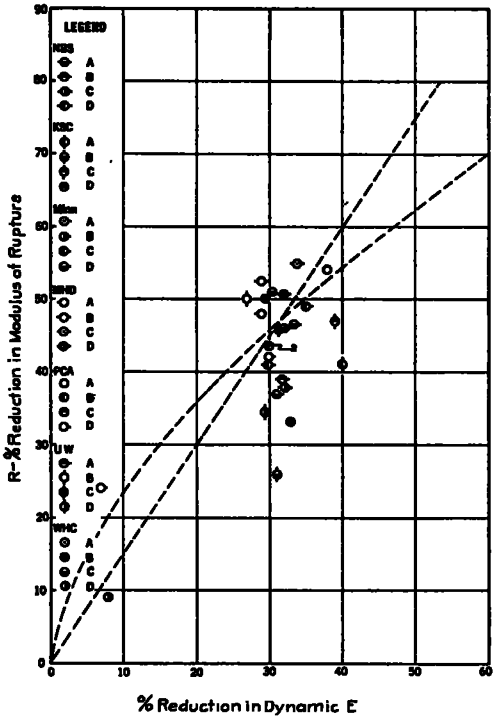

Figure 9. Average R-E Values for Coordinating Programs

a proper gage of the durability of concrete made of an heterogeneous aggregate.

The data of Table 9 and Figure 15 for the Series C coordinating program again shows concrete of excellent and uniform strength. The average percentage reduction in dynamic E for Series C was 33 and the range in laboratory averages 30 to 39. The reduction in modulus of rupture average 47 per cent and the range in laboratory averages was 38 to 55 per cent. In number of cycles there is again a considerable range although five of the seven laboratories report averages of 3 to 6 cycles at failure. The dispersions in numbers of cycles, reductions in E and moduli of rupture are markedly less than those for Series B. Hence, for concrete of low durability, ten specimens appear to give significant results.

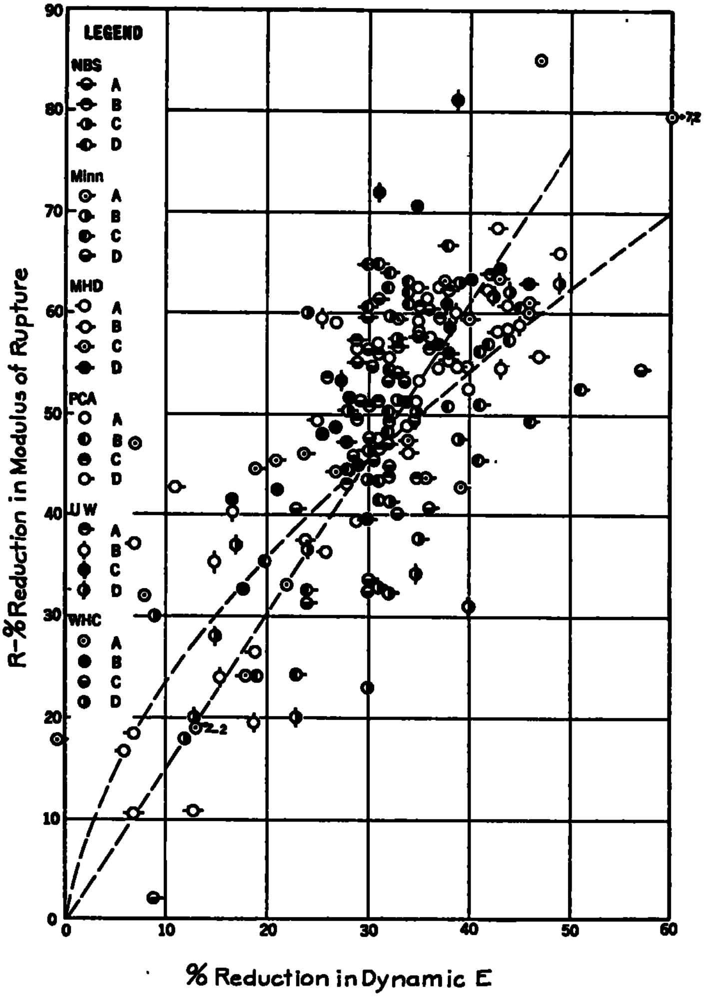

Figure 10. Individual R-E Values for Local Programs

Comparison of Local Test Programs. Table 6 shows that in the local test programs five of the seven laboratories froze specimens partly or wholly immersed in water and the other two laboratories froze them in air. In thawing there is a considerable difference in procedure as noted in that table. The average time required to lower the temperature of specimens from 32° to 15° F. varied from 40 min. for PCA to 214 min. for UW laboratory with the average times for other laboratories running between 82 and 130 min.

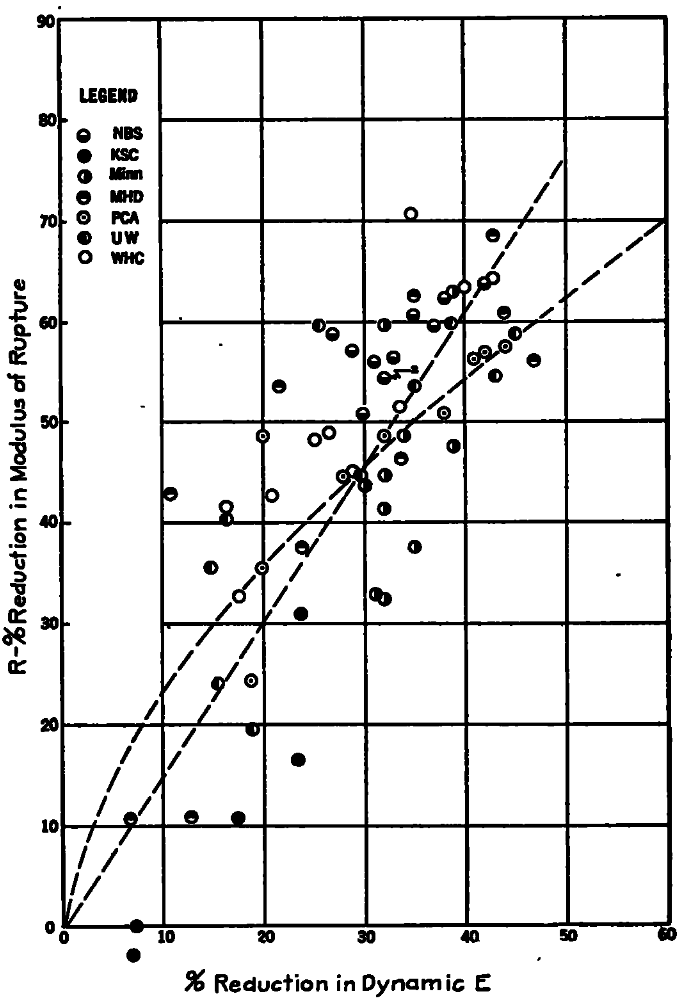

Figure 11. Individual R-E Values for B Series Local Program

Comparing strength and dynamic modulus results for the local programs on the B and C concretes, Table 9, 11, and Figure 16, it is evident that the procedures of NBS and PCA laboratories were speediest and most severe but not discriminatory between the two classes of concrete. The procedures at Minn, MHD and WHC laboratories, though less severe, produced failure within a reasonable number of cycles and also showed good discrimination between the two concretes tested.

Comparison of Coordinating and Local Test Procedures. Considering both coordinating and local programs, none of the programs as run provided a rapid procedure with sufficiently small dispersion of individual test values and a sufficiently high degree of discrimination for a standard. Table 11 based on Table 9 will be found helpful in making comparisons. Of the used procedures, the local WHC, MHD, and coordinating programs most nearly accomplish the desired objective. With still closer control of variables it is believed that the coordinating program can be further developed to attain this end.

Effect of Air Content on resistance of Concrete to Freezing and Thawing. From considerations of the air contents computed for concretes of the A and B[2] coordinating programs, Table 5, and the number of cycles required to produce a reduction of 30 per cent in dynamic modulus, Table 9, it is evident that those concretes with an air content of about 1½ per cent or more are markedly superior in resistance to freezing and thawing. The variation in air content is believed to be largely due to differences in speed and mixing action of the mixers used, see Figures 1(a), (b), and (c).

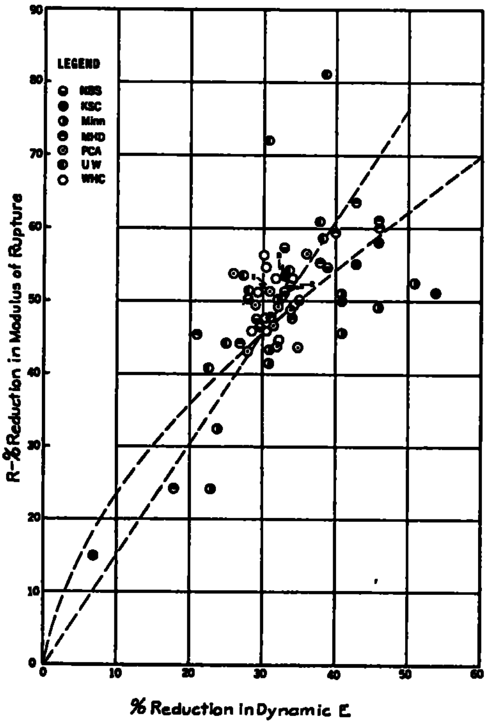

Figure 12. Individual R-E Values for C Series Local Program

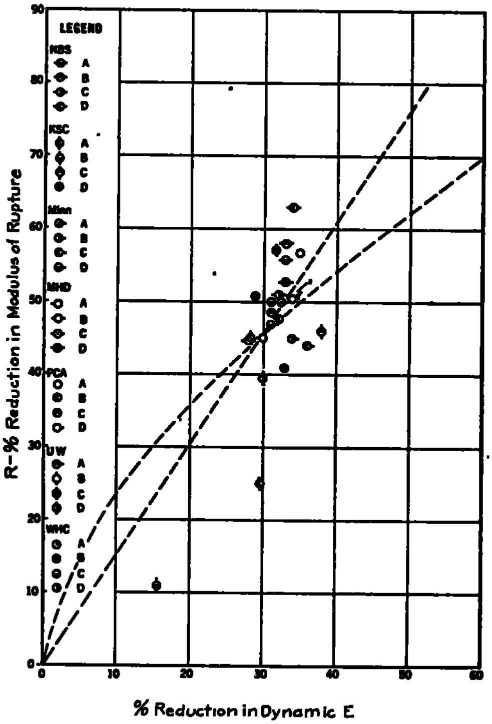

Figure 13. Average R-E Values for Local Programs

The Effect of Prolonged Moist Curing on Resistance to Freezing and Thawing. Extra sets of B and C specimens were made at the PRA laboratory and stored in the moist room for 784 days. Half of each set was then shipped in soaked sawdust to the NBS and WHC laboratories for the coordinating freezing and thawing tests. Table 12 shows the results of the tests on these specimens and the comparable 28-day tests made at each of the laboratories.

It will be observed that all of the long-cured specimens exhibited reductions in dynamic modulus of 30 per cent in from two to seven cycles of freezing and thawing and showed corresponding reductions in modulus of rupture. Such a rapid deterioration of the older C-specimens might be attributed largely to the poor resistance of the Bethany Falls limestone coarse aggregate, but such an explanation does not account for the early failure of the

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[2] It should be noted that no air determinations were made for the specimens in the B program. However, it is reasonable to assume from similarity in mixers and specific weights of hardened concrete that the air content of these specimens was not more than that of A specimens of the PCA laboratory.

TABLE 9

RESULTS OF DYNAMIC MODULUS AND MODULUS OF RUPTURE TESTS ON CONCRETE BEAMS

Beams were loaded at center of a 14-in. span normal to 4-in. face

Lab.	Series	No. Cycles Freez. and Thaw.			Per cent Drop in E (Based on smaller dimension)			Modulus Rupture, lb. per sq. in.					
								Con. Spec.		Frozen & Thawed Spec.			
		Ave.	Range	Ave. Dev.	Ave.	Range	Ave. Dev.	28 da. Ave.	At End of F&T Period	At End of F&T	Per cent Decrease Based on 28 day Ave.		
											Ave.	Range	Ave. Dev.
				%			%						%
NBS	A27-31C	68	53–83	16	31	10–47	33	702	847	441	37	1–63	44
KSC[c]	A1-5C	29	Constant		40	6–65	42	703	670[d]	418	41	10–68	36
Minn[e]	A15-A19C	360	Constant		7	−5–33	133	663	714	504	24	−4–67	69
MHD	A28-31C	19	11–43	53	29	16–43	20	841	863	439	48	19–63	16
PCA[a]	A9-13C	18	3–60	101	38	22–56	19	704	747	325	54	35–66	15
UW	A8-12C	600	Constant		−3	−5–0	45	653	770	705	−8	−17–(−4)	42
WHC	A15-19C	694	Constant		−3	−5–0	79	628	742	663	−6	−30–22	261
NBS	A27-31L	3	2–4	15	33	29–36	7	702	702	306	56	47–61	6
KSC[c]	A3-28L	800	Constant		27	8–47	48	703	875	551	22		22
Minn	A15-19L	501	466–527	6	32	−1–72	35	663	714	332	50	18–80	20
MHD	A28-31L	25	16–52	42	30	17–43	31	841	863	459	46	18–62	28
PCA[a]	A9-13L	4	2–7	45	35	27–44	8	704	747	306	57	52–62	4
UW	A8-12L	600	Constant		−5	−8–(−1)	32	653	770	716	−10	−25–13	95
WHC	A15-19L	542	237–696	38	18	7–47	59	628	742	382	39	19–85	45
NBS	B27-31C	167	120–210	19	32	1–59	65	695	739	421	39	7–70	54
KSC[c]	B1-5C	45	Constant		31	6–65	81	662	764[d]	490	26	−16–68	126
Minn	B15-19C	30	8–40	28	32	15–56	32	656	884	354	46	30–84	29
MHD	B27-31C	34	11–82	69	29	20–36	12	798	830	378	53	43–65	10
PCA	B9-12C	67[b]	40–90	27	30[b]	19–42	27[b]	670[b]	675	379[b]	43[b]	33–54	22
UW	B8-12C	26	17–42	29	27	7–48	45	675	706	337	50	13–73	27
WHC	B15-19C	27	13–45	39	30	11–47	38	720	813	360	50	28–70	23
NBS	B27-31L	4	3–6	19	33	27–42	11	695	695	292	58	51–64	5
KSC[c]	B27-31L	800	Constant		16	6–33	45	662	850	591	11	−3–31	17
Minn	B15-19L	68	47–81	13	34	31–39	8	656	884	360	45	32–63	17
MHD	B27-31L	64	32–122	39	28	7–47	46	798	830	440	45	11–68	35
PCA	B8-12L	9	7–11	15	32	19–44	24	662	714	345	48	24–58	16
UW	B8-12L	309	199–434	22	28	15–43	36	675	706	372	45	20–60	27
WHC	B15-19L	31	13–62	50	29	16–43	26	720	813	355	51	32–71	18
NBS	C27-31C	27	5–43	44	32	8–58	22	804	899	497	38	−28–59	37
KSC[c]	C1-5C	11	Constant	0	39	19–84	58	773	874	412	47	25–79	34
Minn	C15-19C	3	2–4	10	35	27–40	10	794	846	402	49	42–57	9
MHD	C27-31C	6	3–12	40	34	21–44	18	897	930	406	55	41–68	15
PCA	C8-12C	5	3–9	29	30	25–32	5	787	794	448	43	36–51	11
UW	C8-12C	6	3–7	19	31	25–42	12	768	832	417	46	28–61	14
WHC	C15-19C	4	2–5	24	30	19–42	16	854	928	417	51	43–65	12
NBS	C27-31L	2	2–4	24	32	28–39	8	804	804	391	51	46–57	4
KSC[c]	C1-5L	33	Constant	0	38	7–54	33	773	874	420	46	15–58	27
Minn	C15-19L	27	8–47	53	36	23–51	22	794	846	442	44	24–53	16
MHD	C27-31L	8	3–12	40	34	18–46	24	897	930	440	51	25–64	18
PCA[f]	C8-12L	3	3–4	14	31	28–36	8	787	794	406	48	43–56	8
UW	C8-12L	18	12–27	32	32	23–39	15	768	832	331	57	41–72	16
WHC	C15-19L	4	3–5	15	31	29–34	5	854	928	426	50	45–56	7
NBS	D27-31	154	63–240	39	30	12–41	17	772	875	459	41	23–58	31
KSC[c]	D1-5C	45	Constant		33	7–96	76	757	768	506	33	1–92	72
Minn	D15-19C	296	255–325	7	33	27–40	13	789	1,011	423	47	38–57	11
MHD	D28-31C	4	3–5	20	32	28–39	8	981	955	478	51	47–57	6
PCA	D11-12C	29	5–70	70	30	14–44	19	738	903	426	42	31–55	14
UW	D8-12C	194	180–208	7	30	13–52	29	598	860	392	34	−2–78	33
WHC	D15-19C	694	Constant		8	−4–16	84	544	583	496	9	−4–28	108
NBS	D27-31L	5	3–7	20	34	30–45	9	772	772	287	63	61–66	3
KSC[c]	D1-5L	66	Constant		33	15–61	51	757	768	448	41	24–65	20
Minn	D15-19L	202	123–267	16	31	9–57	26	789	1,011	498	37	2–55	26
MHD	D28-31L	4	3–5	17	34	26–46	15	981	955	447	54	41–64	11
PCA	D11-12L	7	4–11	31	34	29–43	11	738	903	366	50	39–57	10
UW	D8-12L	420	352–469	10	30	13–49	39	598	860	363	39	20–63	23
WHC	D15-19L	597	370–696	20	22	9–37	40	544	583	345	37	18–79	44

[a] 12 specimens.

[b] 6 specimens only.

[c] Made only 5 specimens.

[d] 2 specimens.

[e] Terminated before 30 per cent reduction in E.

[f] 9 specimens.

TABLE 10
THE RELATIVE EFFECTS OF FREEZING AND THAWING ON THE MODULUS OF RUPTURE AND COMPRESSIVE STRENGTH OF CONCRETE

Series	Program	Laboratories Considered	Per cent Decrease in Dynamic E		Per cent Decrease in Mod. of Rupture		Per cent Decrease in Compressive Strength	
			Ave.	Range in Lab. Averages	Ave.	Range in Lab. Averages	Ave.	Range in Lab. Averages
A	C	NBS, KSC, Minn, MHD, PCA	29	7 to 40	41	24 to 54	4	−4 to 13
A	L	NBS, KSC, Minn, MHD, PCA, WHC	29	18 to 35	45	22 to 57	14	2 to 31
B	C	All	30	27 to 32	44	26 to 53	8	3 to 12
B	L	All	29	16 to 33	43	11 to 58	9	1 to 28
C	C	All	33	30 to 39	47	38 to 55	8	2 to 12
C	L	All	33	31 to 38	50	44 to 57	11	7 to 19
Average			30		45		9	

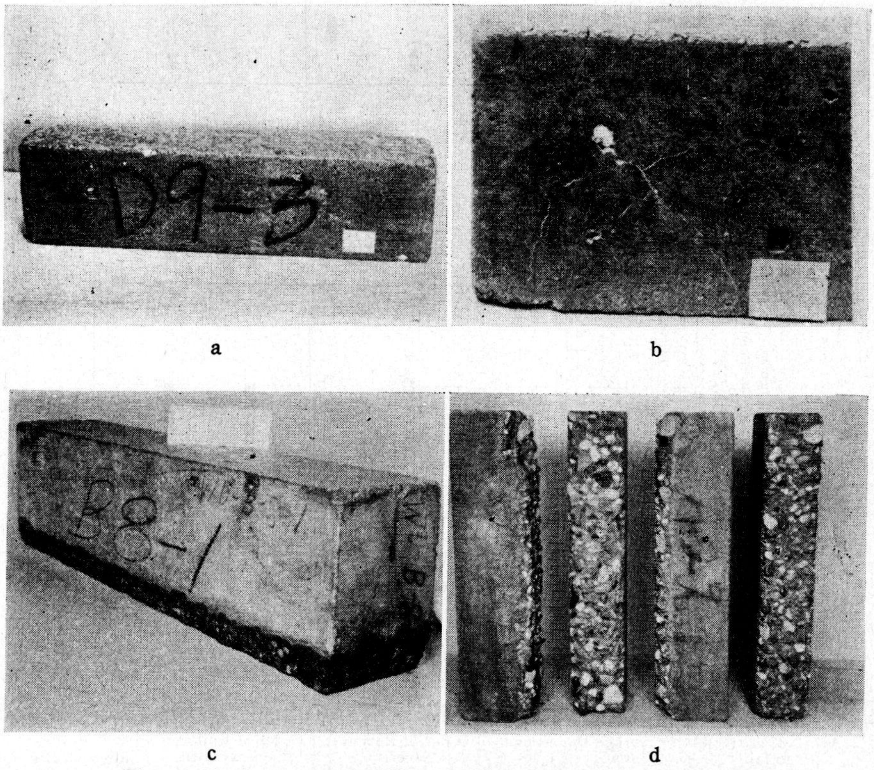

Figure 14. Appearance of Beams After Freezing and Thawing
(a) Upper left. D 9-3 After 380 Cycles in UW Coordinating Program.
(b) Upper right. D 10-2 After 382 Cycles in UW Local Program.
(c) Lower left. B8-1 After 54 Cycles in UW Local Program.
(d) Lower right. A 14, A 17, A 29, A 26 After 670 Cycles in WHC Local Program.

older B specimens made with Potomac River aggregate. Since weight tests on the long-cured B-specimens showed that they had absorbed up to 0.5 per cent more water, by weight, than had the B-specimens cured for 28-days, it appears likely that the more rapid break down of the older B-specimens was due to more complete saturation with water.

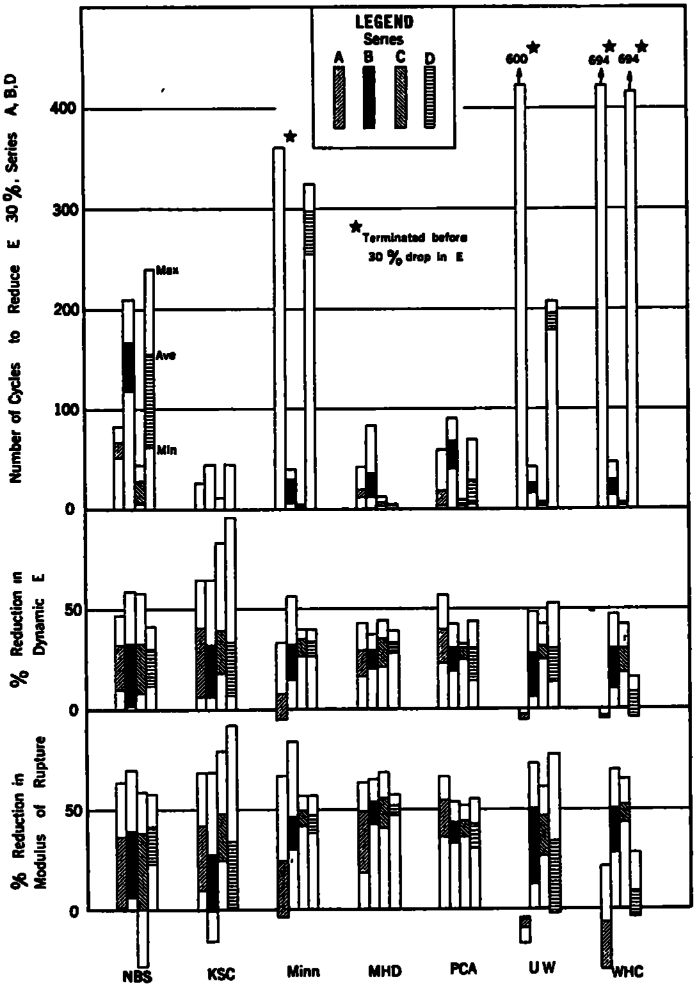

Figure 15. Performance of Beams in Coordinating Programs

TABLE 11
COMPARISON OF LOCAL VERSUS COORDINATE PROGRAMS
C = Coordinate; L = Local

Lab.	Ave. No. of Cycles to fail				Average Deviations in No. of Cycles				Order of Relative Severity				Order of Uniformity of Results				Relative Discrimination, B versus C	
	B-Spec.		C-Spec.		B-Spec.		C-Spec.		B-Spec.		C-Spec.		B-Spec.		C-Spec.			
	C	L	C	L	C	L	C	L	C	L	C	L	C	L	C	L	In C	In L
NBS	167	4	27	2	19	19	44	24	6	1	6.	1	1	3	6	3	Excellent	Poor
KSC	45	800	11	33	0	0	0	0									"	Good
Minn	30	68	3	27	28	13	10	53	3	5	1	6	4	1	1	6	"	Good
MHD	34	64	6	8	69	39	40	40	4	4	4	4	6	5	5	5	"	Excellent
PCA	67[a]	9	5	3	27	15	29	14	5	2	3	2	2	2	4	1	"	Fair
UW	26	309	6	18	29	22	19	32	1	6	4	5	3	4	2	4	"	Good
WHC	27	31	4	4	39	50	24	15	2	3	2	3	5	6	3	2	"	Excellent

[a] 6 specimens only.

Further supporting evidence of the effects of more complete saturation is furnished in the following discussion of the vacuum-pressure treated specimens.

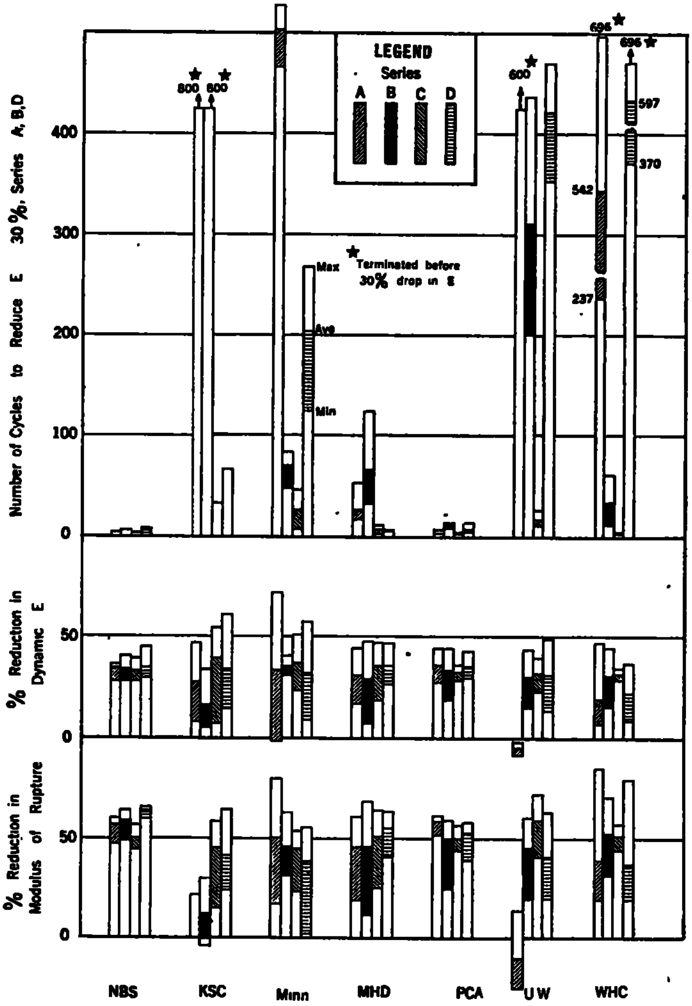

Figure 16. Performance of Beams in Local Programs

Effects of Vacuum-Pressure Treatments on Resistance of Concrete to Freezing and Thawing. The weight and freezing and thawing test data for the A-specimens made with the SR mixer at the UW and WHC laboratories indicated the presence of more air in these specimens than in the B-specimens made at the PRA laboratory with the same Potomac River aggregates and cement. It was, therefore, deemed desirable to ascertain the effect of more complete saturation on these specimens and also on the D-specimens made in the WHC laboratory. This was accomplished by drawing a partial vacuum on the specimens and then immersing them in water under pressure. For each cycle of such V-P treatment, a vacuum of 28 in. of mercury was maintained for 24 hr. followed by water under a pressure of 125–150 lb. per sq. in. for 24 hr. Accordingly the specimens at these laboratories were paired on the basis of like changes in dynamic modulus exhibited after 600 cycles of freezing and thawing. One specimen of each pair was broken in flexure and the average of the results recorded in Table 9. The other specimen of each pair was subjected to the V-P treatments scheduled in Table 13. The data of Table 9 show that the average flexural strengths of the UW A-specimens after 600 cycles of freezing and thawing by either test procedure had increased 8 to 10 per cent over the 28-day values and were about 8 per cent less than the average strength of the 2-year control specimens. Table 9 indicates that the A-specimens tested in the coordinating program at the WHC laboratory also showed an increase in strength of 6 per cent over the 28-day value after 694 cycles of freezing and thawing. In the WHC local program, however, both the A and D specimens exhibited considerable losses in strength after freezing and thawing.

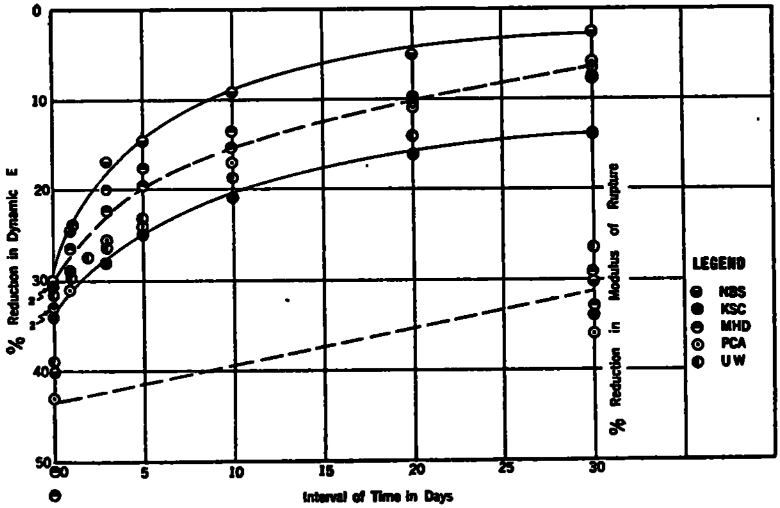

Figure 17. Effect of Water Curing Subsequent to Freezing and Thawing on the Dynamic Modulus of Elasticity of Specimens of Series D Coordinating Program

Consider the UW specimens of the A series which had increased somewhat in strength during the freezing and thawing tests. The data in Columns 6 and 7 of Table 13 show that failure in freezing and thawing promptly followed a V-P treatment which caused an increase in absorbed water approximating 0.16 lb., corresponding to about 1 per cent by weight, or 2½ per cent by volume. From a consideration of the data in Columns 6 and 7 of Table 13 for the beams tested by the WHC laboratory, it will be observed that they also failed after approximately 1 per cent more water had been forced into them by V-P treatments and had then been subjected to freezing and thawing.

Figure 18 shows the average changes in weight during the freezing and thawing tests for all UW specimens. It will be noted that the C-specimens of the coordinating program began to increase in weight immediately after the first cycle and that the C-specimens in the local program started to increase in weight after 10 cycles, whereas all other specimens of the A, B and D series exhibited weight losses until given V-P treatments. The specimens of the UW local program frozen partially immersed in water in nearly all instances suffered greater weight losses than did the corresponding specimens frozen in air in the coordinating program. The losses in weight in the local program of the A and D specimens which had appreciable air contents were much less than the loss in weight in the same program of the B specimens which had very low air contents.

The right hand portion of Figure 18 shows the marked influence of V-P treatments in raising the water content and thus increasing the weights of the A-specimens. The instability of this free water is shown by the losses in weight between V-P treatments which were principally due to release of free water freezing.

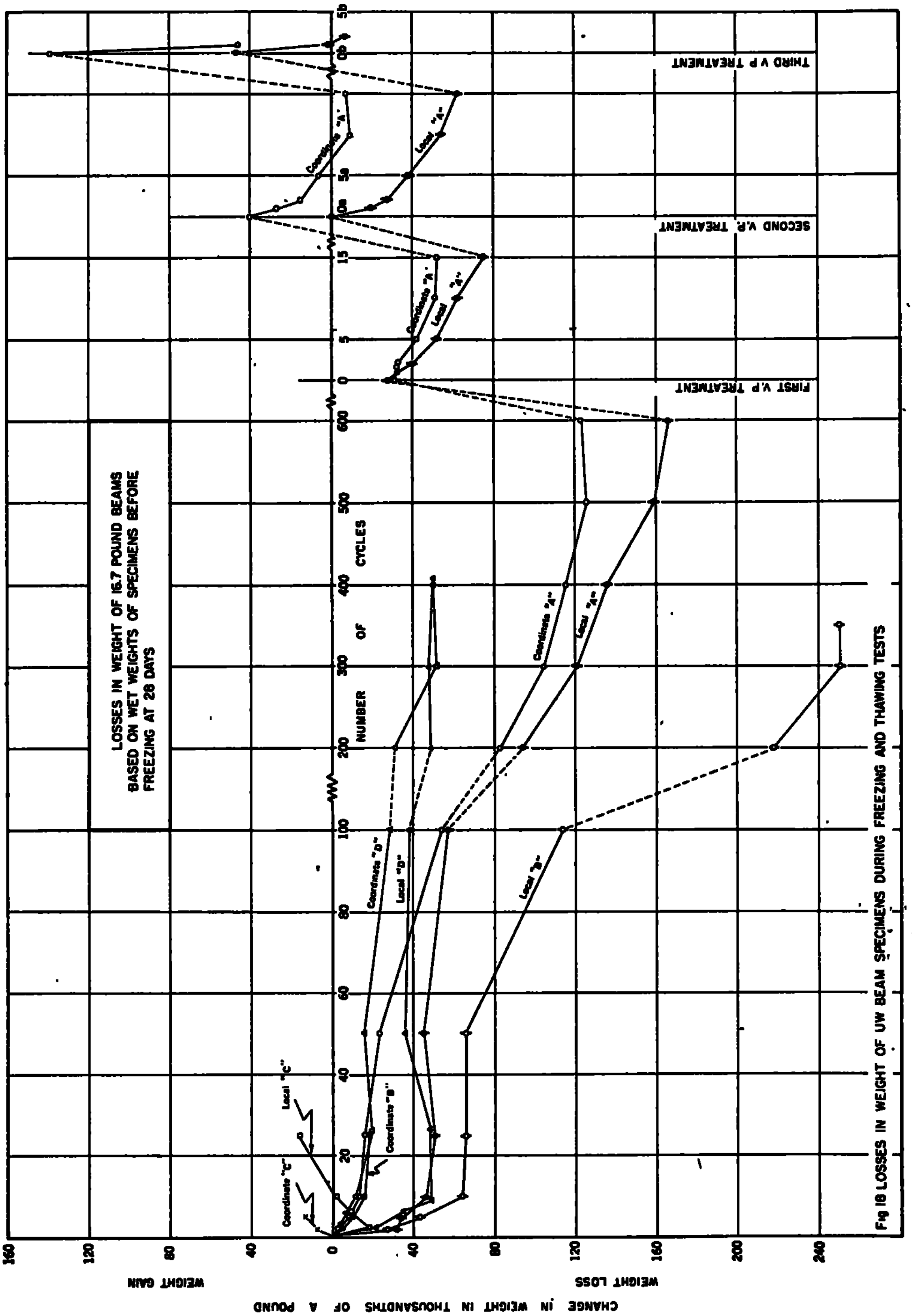

Fig 18 LOSSES IN WEIGHT OF UW BEAM SPECIMENS DURING FREEZING AND THAWING TESTS

Figure 18

The data in Tables 9 and 13 also serve to show the high resistance of such concrete to freezing and thawing when incompletely saturated and the difficulty encountered in saturating. Furthermore these data emphasize the necessity for preparing and conditioning concrete specimens for freezing and thawing tests in such manner that the degree and uniformity of saturation during testing is known and controlled.

Effect of Dried Coarse Aggregate. For the tests of Series D the NBS laboratory used Potomac River sand and gravel. For this series the gravel was oven dried and then soaked in water for 24 hr. This coarse aggregate then contained 0.8 per cent of water, (Table 4) or 0.3 per cent less than the average water content of similar aggregate, not oven dried, used in Series A at the NBS laboratory. A comparison of results of Series A and D (Table 9 and Fig. 15) coordinating program for NBS laboratory, show that the average number of cycles required to produce 30 per cent reduction in the dynamic modulus was increased from 68 for concrete of saturated aggregate to 154 for concrete made of the same coarse aggregate kiln dried and then soaked 24 hr. in water. Furthermore, the range in number of cycles for the beams of concrete of saturated aggregates of Series A was only 53 to 83 while with dried aggregate the range in cycles for beams of Series D was 63 to 240 cycles. On the other hand, the percentages of spread in reductions in the dynamic modulus and modulus of rupture for the saturated concrete specimens were greater than for the concrete made of dried aggregate. For both types of concrete the average reduction in dynamic E was accompanied by comparable reductions in flexural strength.

TABLE 12

RESULTS OF DYNAMIC MODULUS AND MODULUS OF RUPTURE TESTS

Comparison of Data Obtained at Two Laboratories on B and C Specimens Tested in Coordinate Program at 28 Days and After Moist Curing 784 Days. Each Control Average Represents 5 Tests; Other Averages Represent 10 Tests.

Lab.	Series Des. and Program	Age at Test, Days	No. Cycles Freeze. & Thaw.			Per cent Drop in E (Based on smaller dimen.)			Modulus of Rupture, lb. per sq. in.					
									Cont. Spec.		Frozen & Thawed Spec.			
												Per cent Decrease Based on 28 Day Ave.		
			Ave.	Range	Ave. Dev.	Ave.	Range	Ave. Dev.	Ave. at Start	At End of F&T Period	At End of F&T	Ave.	Range	Ave. Dev.
					%			%						%
NBS	B27-31C	28	167	120–210	19	32	1–59	65	695	739	421	39	7–70	54
"	B15-19C	784	2			30	28–37	11	735		435	41	37–50	10
NBS	C27-31C	28	27	5–43	44	32	8–58	22	804	899	497	38	−28–59	37
"	C15-19C	784	2			27	24–33	10	1,015		585	42	35–54	13
WHC	B15-19C	28	27	13–45	39	30	11–47	38	720	813	360	50	28–70	23
"		784	4	2–7	55	30	18–41	18	713		400	44	31–71	18
WHC	C15-19C	28	4	2–5	24	30	19–42	16	854	928	417	51	43–65	12
"		784	2	Constant		33	30–39	7	1,028		481	53	42–64	12

Similar comparisons based on the local programs of Series A and D, NBS laboratory (Table 9 and Fig. 16), again show that the concrete made with the dried coarse aggregate No. 1 was much more durable than that made with the same aggregate not dried previous to soaking.

Effect of Water Curing After Freezing and Thawing on Dynamic Modulus of Elasticity and Modulus of Rupture. Figure 17 shows the trend in the recovery of the dynamic modulus of elasticity of frozen and thawed specimens of Series D when subjected to 30 days curing in 70° F. water. The figure shows that the average dynamic E during this period changed from 69 to 94 per cent of the normal 28-day value due to the water curing treatment. The results indicate that approximately 40 per cent of the 30-day recovery occurred in 5 days and 60 per cent in 10 days. However, the flexural strength only changed from an average value of 56 per cent to an average value of 69 per cent of the 28-day strength during a month of water curing. Hence, the influence of water curing subsequent to freezing and thawing on flexural strength is much less marked than the effect

TABLE 13
EFFECTS OF VACUUM-PRESSURE TREATMENTS ON RESISTANCE TO FREEZING AND THAWING OF CONCRETE BEAMS

Each beam had been subjected to 600 to 693 cycles of freezing and thawing before vacuum-pressure began.

Series Program Laboratory	Per cent Drop in E Prior to V-P (d = 3")	No. of V-P Treatments	No. F & T Cycles After Last V-P Treat.[a]	Change in Wt., lb.			Per cent Drop in E Due to V-P & F & T (d = 3")[c]	Mod. of Rupture, lb. per sq. in.			Comp. Strength, lb. per sq. in.		
				Based on		Max. Gain Without Failure[b]		28-day Control Ave.	After V-P and F & T		28-day Control Ave.	After V-P and F & T	
				28-day Wt.	600+ cyc. Wt.				Ind. Tests	Decrease %		Ind. Tests	Decrease %
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
A Local UW	−1.2	3	2	+0.032	+0.182	+0.163	46	653	294	55	3,950	3,600	9
	−4.5	3	2	+0.030	+0.176	+0.143	44	653	366	44	3,950	4,070	−3
	−6.3	3	2	+0.080	+0.225	+0.147	37	653	396	39	3,950	4,170	−6
	−6.5	2	2	−0.011	+0.159	+0.110	36	653	385	41	3,950	4,420	−12
Ave.	−4.6						41		360	45		4,065	−3
A Coord. UW	−2.7	2	12	+0.004	+0.154	+0.092	41	653	351	46	3,950	4,550	−15
	−3.6	2	4	+0.041	+0.166	+0.105	41	653	399	39	3,950	3,810	4
	−6.2	3	1	+0.139	+0.254	+0.140	62	653	269	59	3,950	4,110	−4
	−3.8	2	1	+0.082	+0.192	+0.087	50	653	257	61	3,950	4,220	−7
	−1.2	2	6	+0.048	+0.183	+0.115	36	653	377	42	3,950	4,070	−3
Ave.	−3.5						46		331	49		4,152	−5
A Local WHC	16.7	1	1				22						
		1	1	−1.060	+0.126	+0.126	29	628	449	28	3,680	2,380	35
	7.6	1	1	−0.630	+0.208		45	628	263	58	3,680	3,110	16
	4.9	1	1				20						
		1	1	−0.934	+0.162	+0.134	44	628	215	66	3,680	2,710	26
	16.0	1	1	−0.930	+0.126		34	628	346	45	3,680	2,320	37
Ave.	11.3						38		318	−49		2,630	28
A Coord. WHC	−2.3	1	1				11						
		1	1				10						
		1	2	+0.012	+0.194	+0.146	53	628	503	20	3,680	3,300	10
	−9.2	1	1				−5						
		1	3				6						
		1	3	+0.008	+0.228	+0.152	29	628	405	36	3,680	3,310	10
	0	1	1				6						
		1	3				20						
		1	1	+0.024	+0.224	+0.160	42	628	300	52	3,680	3,370	8
	−1.2	1	1				4						
		1	3				21						
		1	1	+0.109	+0.270	+0.185	38	628	315	50	3,680	3,250	12
Ave.	−3.2						40		381	39		3,307	10
D Local WHC								544			3,120		
	16.6	1	1				28						
		1	1	−0.752	+0.170	+0.168	45	544	223	59	3,120	2,280	27
	16.8	1	1	−0.268	+0.218		50	544	187	66	3,120	2,820	10
	20.1	1	1	−0.890	+0.114		28	544	335	38	3,120	2,670	14
Ave.	17.8						41		248	54		2,590	17
D Coord. WHC								544			3,120		
	−3.9	1	1				−3						
		1	1				−4						
		1	3				9						
		1	1	−0.054	+0.270	+0.182	35	544	200	63	3,120	2,890	7
	20.1	1	1	+0.009	+0.147		35	544	304	44	3,120	2,890	7
	6.9	1	1				10						
		1	3				20						
		1	1	+0.066	+0.226	+0.146	42	544	320	41	3,120	2,990	4
	14.7	1	2	+0.010	+0.130		33	544	550	−1	3,120	3,390	−9
Ave.	9.4						36		343	37		3,040	3

[a] Fifteen cycles of freezing and thawing were imposed between V-P treatments on UW beams only.
[b] Based on 600+ cyc. wt. These wts. were obtained one treatment previous to treatment causing failure.
[c] Based on original series readings.

of such treatment on the dynamic modulus of elasticity.

In these tests recovery in dynamic E during water curing for one month subsequent to freezing and thawing was 25 per cent of the 28-day value, while the recovery in modulus of rupture was only 13 per cent. Based on the values after freezing and thawing the increases were about 35 and 23 per cent, respectively.

Absorption Test Data. Neither consideration of the reported magnitudes of the absorptions of the control specimens for any period nor the consideration of the rates of absorption of those specimens reflects an index which predicts the reported variations in resistance to freezing and thawing obtained at the different laboratories in the different series of tests under the programs used. Therefore the data although concordant have not been reported herein.

The average 48-hr. absorptions for all laboratories on the 28-day control specimens for the A, B, and C specimens were 2.12, 2.12, and 2.17, respectively; for the specimens after freezing and thawing the corresponding averages were 2.58, 2.58, 3.01, respectively.

From consideration of the relatively uniform absorption characteristics of the aggregates and the nearly constant proportions of the mortars used in these tests together with the data on absorption of the concrete control specimens it would appear that the absorptions and rates of absorption of the control specimens should be approximately the same. This was true. Hence, concretes made of sound aggregates of relatively low absorption and mortars of proportions similar to those used in these programs are not likely to exhibit absorption characteristics which will serve to differentiate between their resistances to freezing and thawing.

It should be noted that the average 48-hour absorptions after freezing and thawing were in all cases greater than the 48-hour absorptions on the corresponding control specimens.

CONCLUSIONS

1. Under the conditions of these tests the electronic vibrating devices used provided a convenient and rapid means of determining the change in the dynamic modulus of elasticity of the specimens tested.

2. Within the limits of these tests the average relation of the percentage decrease in modulus of rupture (R) to the percentage decrease in the dynamic modulus of elasticity (E) due to freezing and thawing was $R = 1.5E$ for either the local or coordinating test procedures. Considering the data of laboratories performing the entire B and C test programs, the individual laboratory average R–E relations were within 20 per cent of the foregoing grand average.

3. The relation between the percentage increase in the modulus of rupture (R′) and the percentage increase in dynamic modulus of elasticity (E′) of the moist-cured control beams was much more variable than the relation between the decreases of these properties in freezing and thawing. Based on changes after 28-days the average relation was $R' = 1.2E'$.

4. For the types of concrete tested the relation between the reductions in flexural strength and in dynamic modulus of elasticity was sufficiently reliable to measure the rate of deterioration of the flexural strength under the methods of freezing and thawing used.

5. The flexural strength is much more sensitive to the deteriorating effects of freezing and thawing than is the compressive strength.

6. Within the limitations of these tests the relation of the reduction in the compressive strength to the reduction in the dynamic modulus of elasticity due to freezing and thawing was so variable in the tests conducted that the reduction in the dynamic modulus could not be used as a measure of the reduction in compressive strength.

7. Loss in weight does not provide a criterion of the early deterioration in flexural strength due to freezing and thawing.

8. Specimens frozen in air as in the coordinating program showed little surface deterioration due to breakdown of the mortar. Some specimens exhibited spalling over unsound coarse aggregate particles.

9. Specimens frozen in contact with water evinced deterioration at the corners and edges and over the portions partially immersed in water.

10. Although there are exceptions, comparison of the local test procedures on the basis of the B and C specimens indicates that in general those procedures in which the rates of freezing from 32° to 15° F. were fast caused failure more quickly than those in which the rates were slow.

11. Those local test procedures having fastest rates of freezing and producing quickest failures did not discriminate clearly between the concretes made of satisfactory and those made of poor coarse aggregate, whereas the procedures in which the rates were somewhat slower and the number of cycles to failure greater provided good discrimination.

12. None of the freezing and thawing procedures tried provided a small dispersion in the number of cycles required for failure and a sufficiently high degree of discrimination to qualify as a standard method. Of the procedures used, the coordinating program, the local WHC, and the MHD are the best, but all exhibit too great dispersions of individual test values to be considered satisfactory. With still better control of the variables it is believed that these dispersions can be reduced and a standard procedure established.

13. The data emphasize the necessity for regulating carefully the methods of making and curing specimens, the air content of the specimens, the degree of saturation of the aggregate at the time of making, and the degree of saturation of the concrete at the time of freezing.

14. Curing of concrete in 70-deg. water subsequent to deteriorating freezing and thawing treatments produces a marked recovery in the dynamic modulus of elasticity but a much less pronounced recovery in flexural strength.

15. In these tests neither the absorption nor the rate of absorption data for the concrete correlated with the differences which the beams exhibited in resistance to freezing and thawing.

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STRUCTURAL TIMBER FOR BRIDGE CONSTRUCTION IN CENTRAL AMERICA

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Although a large part of Central America is covered with forests, the utilization of these woods for the production of bridge timbers and lumber has been extremely limited. In order to determine the suitability of the species in these forests for specific war uses the Coordinator of Inter-American Affairs in cooperation with the Department of Agriculture established the Latin American Resources Project. The personnel for this Project was drawn largely from members of the U. S. Forest Service, including the author, who was assigned to the project from the Forest Products Laboratory.

Of especial concern to the project was the fact that the Pan-American Highway needed timber for bridges, culverts, houses, and other structures to be built in Costa Rica. It was desirable to use, insofar as possible, the woods growing near that highway.

Timbers used in bridge construction must meet definite requirements as to strength and decay resistance. The specific requirements, however, may vary with the type of structure, the location of the timber in the structure, and the type of load the timber is require to carry. Thus, caps require compressived strength perpendicular to the grain; stringers, bending strength and stiffness; floors, stiffness and resistance to abrasion; and piling, decay resistance and adequate compressive strength parallel to the grain. When a wood is known to be deficient in a required property it may be practical to compensate for the deficiency by preservative treatment or by design. Preservative treatment can be applied to nondurable woods and design can provide increased size to compensate for low strength. Since compensating for low joint strength—an important requirement in trusses—is difficult, woods that meet the use requirements without modification are much desired.

The woods in the United States that best meet the requirements of bridge construction are such softwoods as Douglas-fir and Southern yellow pine. The strength properties of these woods have been determined by test at the Forest Products Laboratory, and service records are available for determining their decay resistance. Structural timbers cut from them, are available in standard sizes treated or untreated, and they, as well as other species, are available in stress grades; that is, grades that limit defects in accordance with their effect on strength. Douglas-fir and Southern yellow pine, therefore, furnish most of the bridge timbers used in the United States, although other species are also used, particularly for piling.

No similar information or standards are available for the woods of Central America. The characteristics and properties of a few of the more generally used woods, such as mahogany, or specialty woods, such as lignumvitae or cocobola, are well known from experience with them in numerous uses. The properties and characteristics of most of the other species, and their availability are unknown. They are not manufactured to any given standard of size or quality, and stress grades have not been developed for them. Furthermore, nearly all the woods are hardwoods with characteristics somewhat like

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[1] Maintained at Madison 5, Wisconsin, in cooperation with the University of Wisconsin.