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Effect of Substitutions of Flyash for Portions of Cement in Air-Entrained Concrete

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IT was indicated earlier that substitutions of flyash for up to 25 or 30 percent of the cement in air-entrained concrete resulted in: (1) increase in water-cement ratio, (2) decrease in air content, (3) increase in strength of moist cured concrete at ages beyond 28 days, and (4) decrease in resistance of the concrete to freezing and thawing. The effect of restoring the air content of the concrete containing the flyash substitution by adding an air-entraining agent, not included in the original program, is described in this report.

Materials and procedures in the second series of tests were the same as in the first, except that the aggregates were from a different source and the maximum size was reduced to ¾ in. and the size of the test beams was reduced to 3 by 4 by 16 in.

The results substantiate those of the first series of tests and indicate that in mixes with proportions approximating those in this test, restoring the air content of the concrete has the following effects: (1) reduces the strengths at 7 and 28 days to approximately the same extent as the cement was reduced at 1 yr. and later; however, the strength is equal to or greater than that of the standard concrete; (2) improves the resistance of the concrete to freezing and thawing to a great extent but does not bring it up to that of the standard concrete; and (3) requires considerably more air-entraining agent than normally must be used to develop a like amount of air in regular concrete made with non-air-entraining cement.

● IN our first program of tests in this investigation[1] it was indicated that substitutions of flyash for up to 25 or 30 percent of the cement in air-entrained concrete resulted in: (1) an increase in water-cement ratio, (2) a decrease in air content, (3) an increase in strength of moist cured concrete at ages beyond 28 days, and (4) a decrease in resistance of the concrete to freezing and thawing.

The effect of restoring the air content of the concrete containing the flyash substitution by adding an air-entraining agent, not included in the original program, is described in this report.

[1] Reported in Highway Research Board Proceedings, Vol. 29, 1949.

MATERIALS AND PROCEDURE

The cement and flyash used in this test were from the same sources as those used in the original test. The sand and gravel were from a different source, the Hartland-Verona Sand & Gravel Company, Verona, Wisconsin, and the maximum size of gravel was ¾ in. instead of 1½ in. The gravel was composed of approximately 74 percent dolomitic material, 10 percent igneous material, 7 percent sandstone, and a total of 9 percent chert with 4 percent having a specific gravity less than 2.5. The properties of the materials are given in Tables 1, 2, and 3. The procedures were the same as in the original test except that the size of beam was reduced to 3 by 4 by 16 in. Freezing-and-thawing tests were started when the concrete was 29-days old.

TABLE 1
PROPERTIES OF CEMENT

Time of set	
Initial	3 hr., 15 min.
Final	5 hr., 0 min.
Expansion, autoclave	0.10%
Fineness, Blaine	3,454 sq. cm. per g.
Tensile strength of 1:3 standard mortar	
3 days	240 psi.
7 days	325 psi.
Air content of mortar	19%

TABLE 2
PROPERTIES OF AGGREGATES

	Sand	Gravel
Sieve analysis		
Retained on		
1 in. sieve		0%
¾ in. sieve		6%
½ in. sieve		61%
⅜ in. sieve		—
No. 4 sieve	0%	100%
No. 8 sieve	14%	
No. 16 sieve	34%	
No. 30 sieve	51%	
No. 50 sieve	83%	
No. 100 sieve	98%	
Fineness modulus	2.80	—
Specific gravity	2.60	2.61
Absorption	1.3%	2.4%
Wear, Los Angeles	—	38%
Loss in 8 cycles of sodium sulfate test		15%

TABLE 3
PROPERTIES OF FLYASH

Composition	
SiO_2	44.54%
Fe_2O_3 and Al_2O_3	38.93%
CaO	6.03%
MgO	1.50%
SO_3	2.07%
C	2.0%
Loss on ignition	2.26%
Specific gravity	2.56
Fineness, Blaine	4,170 sq. cm. per g.

Strength and durability tests were made on the following three different concretes: (A) the "standard" concrete made with 5⅓ sacks of air-entraining cement per cubic yard of concrete; (B) concrete made with flyash substituted for 25 percent of the cement in A; and (C) concrete made with the addition of sufficient air-entraining agent (Darex) to B to bring the air content back up to that of the standard concrete (A).

TEST RESULTS AND COMMENT

Data pertaining to the mixes and fresh concrete are given in Table 4. Each value is the average of three individual tests made on three different days. It may be noted that when flyash was substituted for 25 percent of the cement in the standard concrete, the water required per cubic yard was increased from 28.9 gal. to 30.8 gal. for the same slump, and the air content of the fresh concrete was decreased from 5.4 percent to 0.4 percent. To bring the air content back up to that of the standard concrete, it was necessary to add air-entraining agent at the rate of 4.68 oz. per sack of cement, considering the flyash as cement. Compared with the amount of agent used in a test made on air-entraining agents, this is about three times as much as was required to obtain a like amount of air in regular concrete made with non-air-entraining cement. With restoration of the air content, the water required was reduced to 29.1 gal. per cu. yd., or practically the same as for the standard concrete. However, the slump of the concrete was 2¼ in. compared to 1¾ in. for the standard, indicating that it still was slightly wetter than the standard.

The strength-test results obtained on moist-cured and frozen and thawed concrete are given in Table 5, and are shown graphically in Figures 1 and 2 for transverse and compressive strengths respectively. The so-called standard concrete showed good strength and durability. After 431 cycles of freezing and thawing it had a transverse strength of 678 psi. which was 93 percent of its 28-day strength and 67 percent of its transverse strength when continuously moist cured to the same age. It had a compressive strength of 5,070 psi. which was 113 percent of its 28-day strength and 82 percent of its compressive strength when continuously moist cured to the same age.

Concrete B, with a 25-percent substitution of flyash but with no added air-entraining agent, up to 28 days had transverse and compressive strengths equal to or as much as 14 percent greater than those of the standard concrete. It subsequently had a gradual gain in relative strength so that at 22 mo. the transverse strength was about 134 percent and the compressive strength about 153 percent of the corresponding strengths of the standard concrete. However, the resistance of Concrete B to freezing and thawing was much less than that of the standard concrete. After 5 cycles of freezing and thawing it had a transverse strength of 195 psi, which was 27 percent of responding strengths of the standard concrete. But after 5 cycles of freezing and thawing it had a transverse strength only 29 percent and a compressive strength 88 percent of the corresponding strengths of the standard concrete after 431 cycles.

TABLE 4
DATA PERTAINING TO MIXES AND FRESH CONCRETE

Properties	A "Standard" Mix Using Air-Entraining Cement	B Flyash Substituted for 25% of Cement in Standard Mix (A)		C Air-Entraining Agent Added to Mix (B) to Bring Air Content Back Up to That of Standard Mix (A)	
Mix. proportions by weight	1:2.22:3.96				
Air-entraining agent, oz. per sk. of cement[a]	—	—		4.68	6.25
Cement factor, sks. per cu. yd.[a]	5.33	5.56	4.18	5.28	3.96
Water-cement ratio by volume[a]	0.723	0.740	0.986	0.735	0.979
Water, gal. per cu. yd.	28.9	30.8		29.1	
Slump, in.	1¾	1¾		2¼	
Air content, percent	5.4	0.4		5.6	

[a] Where two values are given for air-entraining agent, water-cement ratio and cement factor, the first one is computed considering the flyash as cement and the second is based on actual cement only.

TABLE 5
STRENGTH DATA

Properties	A Standard Mix Using Air-Entraining Cement	B Flyash Substituted for 25% of Cement in Standard Mix (A)	Ratio B/A	C Air-Entraining Agent Added to Mix (B) to Bring Air Content Back Up to That of Standard Mix (A)	Ratio C/A
Transverse strength					
a. Moist cured 7 da., psi	463	517	1.12	376	0.81
b. Moist cured 28 da., psi	731	718	0.98	541	0.74
c. Moist cured 658 da., psi	1009	1351	1.34	1070	1.06
d. After 431 cycles of freezing and thawing, psi	678	195[a]	0.29	419	0.62
e. Ratio d/b	0.93	0.27		0.77	
f. Ratio d/c	0.67	0.14		0.39	
Compressive Strength					
a. Moist cured 7 da., psi	2840	3080	1.08	2010	0.71
b. Moist cured 28 da., psi	4490	5130	1.14	3340	0.74
c. Moist cured 658 da., psi	6170	9470	1.53	6570	1.07
d. After 431 cycles of freezing and thawing, psi	5070	4450[a]	0.88	3720	0.73
e. Ratio d/b	1.13	0.87		1.11	
f. Ratio d/c	0.82	0.47		0.57	

[a] The drop in sonic modulus was so rapid that these specimens were tested after 5 cycles of freezing and thawing at age of 35 days. The companion specimens in the moist closet were not tested until the end of the program when other moist cured specimens were tested.

its 28-day strength, and 14 percent of its strength when moist cured for 22 mo. The compressive strength was 4,450 psi. which was 87 percent of its 28-day strength and 47 percent of its compressive strength when moist cured for 22 mo. Looking at it another way, Concrete B under moistcuring conditions at 28 days had transverse and compressive strengths about equal to and, at 22 mo., 134 percent and 153 percent of the cor-

Adding an air-entraining agent to Concrete B and bringing its air content up to that of the standard concrete, as in Concrete C, reduced the strength so that at 7 and 28 days the transverse and compressive strengths were between 70 and 80 percent of the corresponding strengths of the standard concrete. After 28 days, Concrete C gained in relative strength, so at 22 mo. the transverse and compressive strengths were slightly (6%) higher

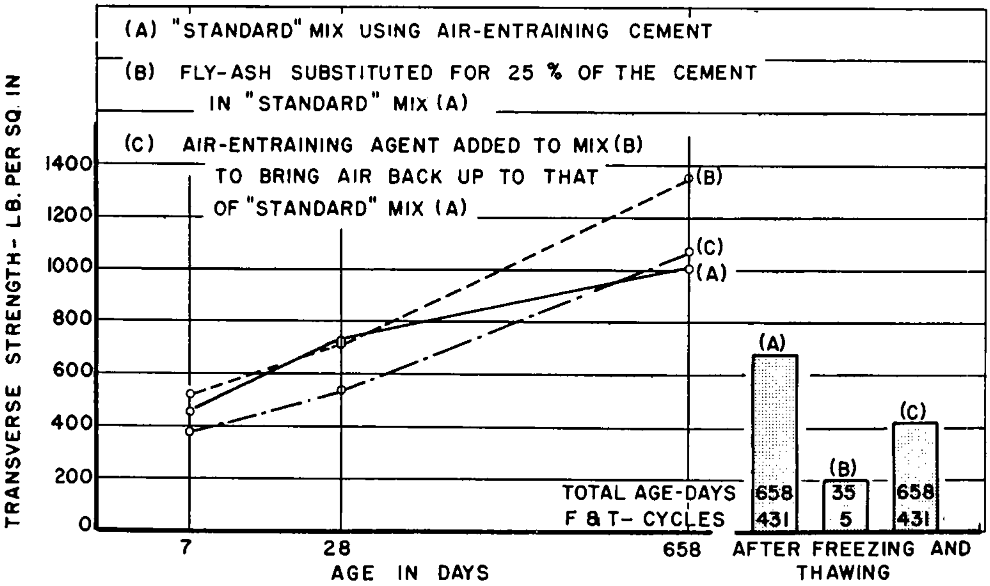

Figure 1. Transverse strength at various ages and after freezing and thawing.

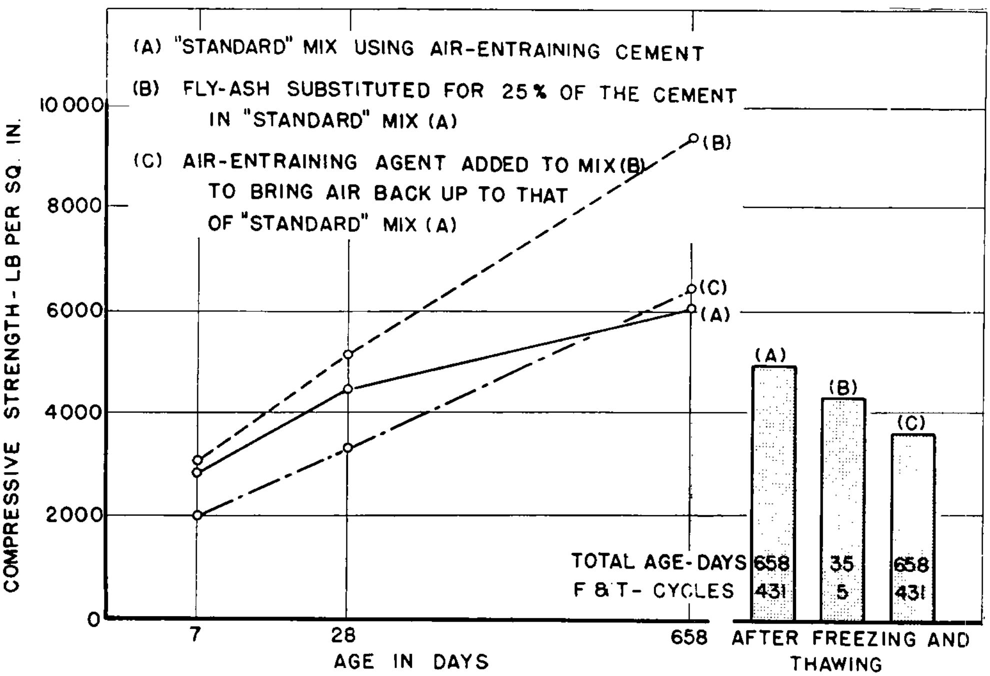

Figure 2. Compressive strength at various ages and after freezing and thawing.

than those of the standard concrete. The durability of Concrete C, as measured by its resistance to freezing and thawing, was much better than that of Concrete B. After 431 cycles, Concrete C had a transverse strength of 419 psi., or 77 percent of its 28-day strength and 39 percent of its strength under moist curing for 22 mo., as compared to 27 and 14 percent for Concrete B after 5 cycles. It had a compressive strength of 3,720 psi., or 111 per-

TABLE 6

CHANGES IN SONIC MODULUS OF INDIVIDUAL SPECIMENS DURING FREEZING AND THAWING

Spec. No.	Number of cycles of freezing and thawing																
	1	3	5	11	20	30	40	70	100	140	170	220	270	320	360	400	431
(A)—"Standard" mix using air-entraining cement[a]																	
1D	−5.3	−8.2	−8.2	−7.6	−5.9	−5.3	−3.6	−1.2	−1.2	+0.6	+1.2	+3.1	+3.0	−2.2	−2.2	−3.3	−5.0
4D	−5.4	−6.0	−6.6	−6.6	−4.8	−3.1	−1.8	−0.6	0	+0.7	+2.5	+5.0	+6.4	+1.9	+1.9	+1.9	+1.3
7D	−6.1	−7.0	−7.0	−5.5	−4.2	−3.6	−1.9	0	+0.6	+1.2	+2.5	+3.7	+4.9	0	−1.2	−1.9	−2.4
Av.	−5.6	−7.1	−7.3	−6.6	−5.0	−4.0	−2.4	−0.6	−0.2	+0.8	+2.1	+3.9	+4.8	−0.1	−0.5	−1.1	−2.0
(B)—Flyash substituted for 25% of the cement in the standard mix (A)[b]																	
2D	−22.2	−45.9	−61.5														
5D	−23.6	−50.9	−65.1														
8D	−25.5	−51.3	−66.5														
Av.	−23.8	−49.4	−64.4														
(C)—Air-entraining agent added to mix (B) to bring air content back up to that of the standard mix (A)[a]																	
3D	−5.9	−8.6	−8.6	−7.6	−5.4	−3.7	−2.5	+0.5	+1.8	+4.4	+6.9	+8.7	+8.0	−1.2	−12.8	−25.6	−35.4
6D	−5.6	−6.3	−6.3	−6.3	−4.6	−2.3	−0.5	+1.7	+1.0	+2.3	+2.3	+3.6	+3.0	−3.4	−9.0	−16.8	−22.0
9D	−4.6	−5.7	−5.7	−4.6	−4.0	−1.6	+0.6	+2.0	+2.6	+3.2	+3.2	+3.8	+2.6	−4.3	−11.2	−18.0	−26.7
Av.	−5.4	−6.9	−6.9	−6.2	−4.7	−2.5	−0.8	+1.4	+1.8	+3.3	+4.1	+5.4	+4.5	−3.0	−11.0	−20.1	−28.0

[a] Tested after 431 cycles of freezing and thawing at age of 658 days.
[b] Tested after 5 cycles of freezing and thawing at age of 35 days.

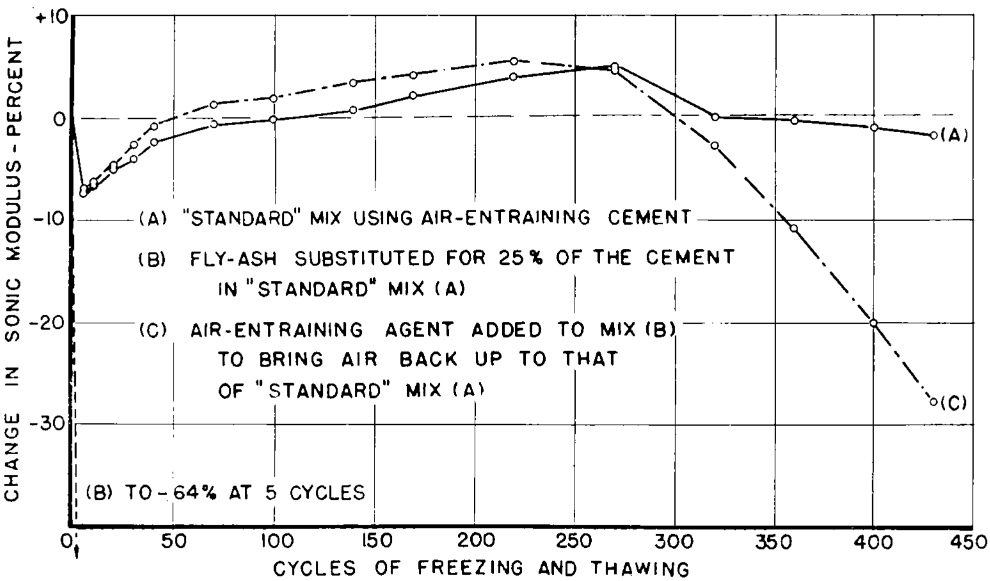

Figure 3. Changes in sonic modulus with freezing and thawing.

cent of its 28-day strength and 57 percent of its compressive strength under moist curing for 22 mo., as compared to 87 and 47 percent for Concrete B after 5 cycles.

A better idea of what actually happened during the freezing-and-thawing test can be obtained by studying the data in Table 6 and the curves in Figure 3, representing changes in the sonic moduli of the concrete beams at intervals during the test. All concretes showed a rather sharp drop in sonic modulus with the very first few cycles. The sonic modulus of Concrete B, which contained the flyash and had an air content of only 0.4 percent, continued to drop very rapidly, so at 5 cycles it had dropped 64 percent and the specimens were removed and tested for strength. In contrast, the sonic moduli of the standard concrete and Concrete C with the flyash substitution and restored air content, gradually recovered after the first four or five cycles, so that the sonic moduli later reached values about 5 percent higher than they were at the beginning of freezing and thawing. At about 220 cycles, however, the flyash concrete ceased to gain and at about 270 cycles both began to drop. Beyond this point the sonic modulus of Concrete C dropped quite rapidly, while that of the standard concrete dropped very slowly, until at 431 cycles the former had dropped 28 percent and the latter only 2 percent from their respective original values.

In discussing the significance of freezing-and-thawing-test data in his paper "Considerations Involved In The Making of Freezing-And-Thawing Tests on Concrete," published in ASTM *Proceedings*, Vol. 46, 1946, Dean Withey, of the College of Engineering of the University of Wisconsin, stated that during a 10-yr. outdoor-exposure test on concrete cylinders in contact with the ground, their time-temperature records indicated the specimens suffered about 250 cycles of freezing and thawing. He also stated that other data from tests on masonry materials lead to the conclusion that accelerated freezing-and-thawing tests conducted with the specimens partly immersed in water, which is the type used in our laboratory, are many times more severe than the action of nature. Judging from this, it would seem that when exposed outdoors in our locality, where there would be approximately 25 cycles of freezing and thawing during the winter and a rest period of several months duration under favorable conditions during the summer, concrete that can withstand 250 cycles of accelerated freezing and thawing with little or no damage should last a long time.

SUMMARY

The results obtained in this second series of tests substantiate the general results obtained in the original series, i.e., substitution of flyash for approximately one fourth of the cement in air-entrained concrete increases the water-cement ratio, decreases the air content, increases the strength at ages beyond 28 days, and decreases its resistance to freezing and thawing. They indicate further that restoring the air content of the concrete containing flyash in the manner and under the conditions of this test: (1) reduces the strength of the concrete at 7 and 28 days to approximately the same extent as the cement was reduced (however, under continued moist curing the strength at about one year is equal to and subsequently becomes slightly higher than that of the standard concrete); (2) restores the resistance of the concrete to freezing and thawing to a great extent, but does not bring it up to that of the standard concrete; and (3) requires considerably more air-entraining agent than normally is required to develop a like amount of air in regular concrete made with non-air-entraining cement.

Delaying the start of the freezing-and-thawing test for several months, or possibly a year, under conditions favorable for the reaction between the flyash and liberated lime, to allow Concrete C to attain a strength about equal to that of the standard concrete might change the durability results. This point could be determined only by further investigation.

DISCUSSION

NORMAN H. WITHEY, *Consulting Engineer, Chicago Fly Ash Company*—Certain of the results reported in this paper are not in strict agreement with the results of tests conducted at several other laboratories using flyash from the same source. A report of some groups of tests conducted at the University of Wisconsin Materials Testing Laboratory has been included in a paper by Prof. G. W. Washa and myself recently submitted to the American Concrete Institute for publication. Our tests showed that the 28-day compressive strength obtained with mixes containing 20 percent of Chicago flyash, by weight of the total cement plus flyash, ranged from 87 to 96 percent of the control mixes containing no flyash. (The same total weight of cement plus flyash was used in both cases.) These percentages may be compared with the values of 70 to 80 percent obtained in the tests reported by Mr. Larson when 25 percent flyash was used. Normally, in mixes where high 28-day compressive strength is of major importance, I recommend that not more than 20 percent of the cement be removed.

In discussing the freeze-and-thaw tests results, I should like to refer to two groups of tests carried out to 500 cycles by Professor Washa which showed that concrete containing Chicago flyash was just as resistant as comparable concrete made without flyash. Also, in a paper previously presented at these meetings, Mr. R. E. Bollen of the Nebraska Department of Roads and Irrigation concluded that the flyash used in his tests improved the resistance of concrete to freezing and thawing action.

In Mr. Larson's paper, two things were mentioned that might have a bearing on the apparent differences:

(1) The coarse aggregate consisted of gravel containing a percentage of chert very near the maximum permitted by their specifications. In Professor Washa's tests, the coarse aggregate was a gravel from Eau Claire, Wisconsin, which contains no chert and which has produced concrete of exceptionally good durability. Perhaps when chert is present, the long-time resistance of concrete to freezing and thawing is materially influenced by the strength of the paste even though the concrete is air entrained. You may recall that Mr. Larson's tests showed 20 to 30 percent less strength in the air-entrained mixes containing flyash than in the control mixes.

(2) The water contents for the air-entrained mixes containing flyash were just slightly higher than for the corresponding mixes without flyash. However, Mr. Larson's paper also pointed out the fact that the slumps of air-entrained flyash mixes were on the upper side of the 2 ± ½-in. range, whereas the slumps for the air-entrained control mixes were on the low side of the range. In Professor Washa's tests, the water contents of mixes containing flyash were 1 to 2½ gal. per cu. yd. less than for corresponding mixes without flyash. Other published reports showing a reduction in water requirement with the use of this flyash are:

(a) Properties of Cement and Concretes Containing Fy Ash by R. E. Davis, R. W. Carlson, J. W. Kelly, and H. E. Davis. ACI *Journal*, May–June 1937.

(b) Use of Chicago Fly Ash in Reducing Cement-Aggregate Reaction by C. H. Scholer and G. M. Smith. ACI *Journal*, February 1952.

(c) Fly Ash as a Pozzolan by R. F. Blanks. ACI *Journal*, May 1950.

(d) Pozzolans in Sand-Gravel Aggregate Concrete by C. A. Sutton and R. E. Bollen. (see p. 317 of this volume of HRB PROCEEDINGS).

Although this difference in relative water content of flyash and nonflyash concretes does not apprear to be large, it undoubtedly had a bearing on the difference in relative strengths obtained. In turn, it seems quite possible that the difference in strengths could be responsible for the difference in behavior of the air-entrained concretes after a large number of freezing-and-thawing cycles. To say this another way, air entrainment is of primary importance to high-frost resistance, as demonstrated in Mr. Larson's paper. His tests showed that properly air-entrained concretes all withstood at least 270 cycles, whereas nonair-entrained concretes failed in 5 cycles; but if the test is carried far enough, differences in strength may influence the eventual results.

One other point should be mentioned. The paper contains the remark that if the freezing-and-thawing tests had been delayed for several months or possibly a year so that the strengths were more nearly equal at the start of freezing and thawing, the picture might have been altered. I believe this is entirely possible, but there is another way that the strengths can be made equal, even at age of 28 days or earlier. It is admitted that if the 28-day compressive strength of the flyash concrete is to be equal to or to exceed the 28-day compressive strength of comparable concrete made without flyash, a certain percentage of cement generally cannot be directly replaced by an equal weight of flyash; rather, a larger quantity of flyash must be used than the amount of cement removed, the extra quantity of flyash being compensated by a reduction in sand. In other words, by redesign of the mixes, the 28-day strengths of the air-entrained fly-ash and nonflyash concretes could be made about equal, which might also change the final results of the freezing-and-thawing tests.

Report of Committee on Curing of Concrete Pavements

J. H. SWANBERG, *Chairman of Committee; Engineer of Materials and Research Minnesota Department of Highways*

THIS report is a summary of replies to a questionnaire prepared by the Committee on Curing of Concrete Pavements and sent to each state and to five federal agencies. Information was received on such items as 1) curing methods permitted and extent of their use, 2) test methods, acceptance limits, kinds, rate of application and preferences of membrane-forming compounds, 3) provisions governing the opening of pavements, 4) order of preference of curing methods or materials, and 5) special conditions provided for curing concrete in cold weather.

The response to the questionnaire was excellent. The data indicate that the most-popular methods on the basis of extent of use are membrane-forming compounds, waterproof paper, and wet burlap, followed by earth, hay, or straw. The preference of clear and pigmented membrane compounds is about equally divided. The rate of application of membrane compounds showed considerable variation with about half requiring a rate of not more than 200 sq. ft. per gal. of compound. The test methods and acceptance limits of membrane compounds varied considerably.

There was not much agreement as to preference of curing methods or materials. A substantial difference was found in the provisions governing the opening of pavements both from the standpoint of strength or age of the pavement. There was closer agreement on the requirements for curing of concrete in cold weather.

● THIS committee, which is concerned with the study of all factors relating to the curing of concrete in pavements, was organized in 1928. Since that time a number of committee reports have been submitted. The committee has also sponsored a number of papers presented before the Highway Research Board which have been a valuable contribution to the knowledge in this field. During the war the committee prepared "Curing Concrete Pavements under Wartime Restrictions on Critical Materials," Wartime Road Problems No. 1, July 1942. Since the war this bulletin has been revised as Current Road Problems 1-R, "Curing of Concrete Pavements," (October 1952).

In accordance with the assigned scope of the activities of the committee it has recently made a national survey of curing methods to obtain an indication of current trends in the use of materials and methods. The committee prepared a questionnaire which was sent to each state, the District of Columbia, the Corps of Engineers, the Bureau of Yards and Docks, the Bureau of Reclamation, and the Civil Aeronautics Administration. The response was excellent in that replies were received from all of the 53 to whom the questionnaire was sent.

QUESTIONNAIRE RESULTS

The questionnaire requested information concerning the methods and materials used by the state or agency in the curing of con-