EFFECT OF SUBSTITUTIONS OF FLY-ASH FOR PORTIONS OF THE CEMENT IN AIR-ENTRAINED CONCRETE

GUY H. LARSON, *Materials Engineer, State Highway Commission of Wisconsin*

SYNOPSIS

Tests were made to study the effects on properties of air-entrained concrete of substituting fly-ash for portions of the cement

The properties studied included water requirement, air content, strength and durability as indicated by resistance of the concrete to freezing and thawing The program included tests on concretes of two different consistencies—approximately 2- and 6-inch slumps—having nominal cement contents of 3, 4½ and 6 bags per cubic yard, each with substitutions of fly-ash for 0, 15, 25 and 35 percent by weight of the cement.

An air-entraining cement was used with commercially produced sand and gravel which were dolomitic in character and of good quality The fly-ash was obtained from an utility power plant in the vicinity of Chicago, Illinois Specimens consisted of 4-in. by 4-in. beams, moist cured and tested at various ages and after a freezing and thawing test The latter consisted of alternately freezing specimens at −10 F in trays with ½ to ¾-inches of water, and thawing at room temperature.

The results of the test indicate that within the range covered, the effects of increasing substitutions of fly-ash for cement in air-entrained concrete in general are to (a) increase the water-cement ratio, (b) decrease the air content, (c) increase the strength of moist cured concrete at ages beyond 28 days, with a probable optimum substitution of fly-ash around 25 to 35 percent, and (d) to increase the loss in strength due to freezing and thawing.

Many consumers were looking for some means of conserving portland cement during the acute shortage about two years ago Reports indicated that various pozzolanic materials had certain beneficial effects on concrete and might be used to advantage. The State Highway Commission of Wisconsin became interested in fly-ash and a review of the reports of tests by Professor R. E. Davis and associates at the University of California, published in the May–June 1937 and January 1941 American Concrete Institute Journals indicated that the material had considerable merit. It was therefore decided to investigate the effects of substitutions of fly-ash for portions of the cement on the properties of concrete using materials available locally.

The investigation included a study of the effects of substitutions of fly-ash for portions of the cement in air-entrained concrete on: water requirement, air content, modulus of rupture and compressive strength, and durability (resistance to freezing and thawing).

TEST PROGRAM

The program included tests on concretes of two different consistencies—approximately 2-in. and 6-in. slumps—having nominal cement contents of 3, 4½ and 6 bags per cubic yard, each with substitutions of fly-ash for 0, 15, 25 and 35 percent by weight of the cement.

Specimens consisted of 144 4- by 4-in. beams, one half of which were 36 in and the other half 27 in. in length. The former provided tests at 3 and 7 days, and after continuous moist curing until termination of the freezing and thawing test. The latter provided tests at 28 days, and after the remaining portion of the beam had been subjected to the freezing and thawing test Ends broken off the beams in the transverse tests were tested in compression as modified cubes the following day

MATERIALS

The cement used was Universal-Atlas air-entraining cement (Type 1-A) and was purchased from a local fuel and materials dealer. The aggregates were sand and gravel of good quality produced by the Capitol Sand & Gravel Company from a deposit in the vicinity of Madison, Wisconsin. The gravel was generally dolomitic (85–90 percent) with some igneous material and a small amount of cherty material. The coarse particles in the sand were dolomitic but the finer particles were largely quartz. The fly-ash was a by-product of the State Line Power Plant of the Commonwealth Edison Company, Chicago, Illinois. Madison city water was used in the concrete. The results of routine tests made on the materials are given in Tables 1, 2 and 3.

TABLE 1
PROPERTIES OF CEMENT

Time of Set	
Initial	3 hr 15 min.
Final	5 hr 00 min.
Expansion, Autoclave	0 10 percent
Fineness, Blaine, sq cm per g	3454
Tensile Strength of 1 3 Standard Mortar	
3 day	240 psi.
7 day	325 psi
Air Content of Mortar	19 percent

TABLE 2
PROPERTIES OF AGGREGATES

	Sand	Gravel	
		No 1	No 2
Gradation			
Percent Retained on 1½ in Sieve			0
" " " 1 in "			50
" " " ¾ in "		0	92
" " " ½ in "		57	100
" " " ⅜ in "		78	
" " " No 4 Sieve	1	100	
" " " No 8 "	13		
" " " No 16 "	32		
" " " No 30 "	47		
" " " No 50 "	82		
" " " No 100 "	96		
Absorption, percent	1 0	1 6	
Specific Gravity	2.65	2 71	
Wear, Los Angeles, percent		40	

TABLE 3
PROPERTIES OF FLY-ASH

	Shipment No 1	Shipment No 2[a]
Composition, percent		
SiO_2	49 67	44 54
Fe_2O_3 & Al_2O_3	40 69	38 93
CaO	4 13	6 03
MgO	1 36	1 50
SO_3	1 46	2 07
C	0 63	2 00
Loss on Ignition, total	1 25	2 26
Specific Gravity	2 56	2 56
Fineness, Blaine, sq cm per g	3695	4170

[a] Shipment No 2 was appreciably darker in color than No. 1

PROCEDURE

Theoretical quantities of materials for the concretes with different cement contents were estimated on an air-free basis, and the actual cement content computed after the concrete had been mixed and the air content determined by test.

The coarse aggregate was separated into two sizes, No. 4 to ¾-in and ¾- to 1½-in , and recombined in the proportion of 40 percent of the former and 60 percent of the latter when weighing materials for individual batches. Prior to mixing, all the aggregates were immersed in water at room temperature for 24 hr , after which the sand was drained and brought to a near surface dry condition, the amount of remaining water determined by test and sufficient moist sand weighed out to provide the proper amount of dry sand while the coarse aggregates were weighed under water. The free water in both coarse and fine aggregates was considered a part of the mixing water.

A small tilting drum mixer of 1½ cu. ft. capacity with three radial blades was used for mixing. The drum was rotated at a speed of 16 rpm. The aggregates and cement were placed in the drum in that order, and mixed dry for ½ min When substitutions of fly-ash were made the fly-ash was added with the cement. Finally the water was added and the batch mixed for 1½ min. The consistency of the concrete was observed in the mixer and slight adjustments were made in the quantity of water in an effort to maintain the same slump in succeeding batches.

Upon completion of mixing the batch was dumped into a metal pan and turned twice with a shovel. The air content of the freshly mixed concrete was determined by means of a pressure air meter. While the bowl of this apparatus was being filled, a slump test was also being made. The concrete used in the air test was discarded, but that used in the slump test was returned to the batch which again was turned with shovels, and the beam specimens molded.

When molding beams the molds were filled in two equal layers. Each layer in the 36-in beam was rodded 50 times and in the 27-in. beam 40 times with a ⅝-in. bullet-nosed puddling rod. The sides and ends were spaded with a mason's trowel, and the final layer was struck off with a wood screed and finished with a steel trowel.

After molding, specimens were covered with wet burlap and allowed to set for 20 hr. At the end of this time, the molds were removed and the specimens placed in the moist room and cured at 70 F. in fog (100 percent relative humidity) until tested. Some of the beams with very low cement contents could not stand handling at one day. In these cases the side pieces of the molds were removed and the specimens carried into the moist room and left on the steel channel bases until the second or third day.

Concrete was mixed on six different days, the 2-in slump and 6-in. slump concretes alternating. Specimens were made to provide for one test under each condition each day, so that the values in the summaries would represent an average of three tests on specimens made on different days In some cases specimens were broken accidentally and consequently some values represent but one or two tests.

After 28 days of moist curing, specimens intended for the freezing and thawing test were immersed in water for 24 hr. At the end of this immersion period, they were placed in trays in water to a depth of $\frac{1}{2}$ to $\frac{3}{4}$ in. with their finished surfaces up and with approximately 1 in. of space on all sides. The trays were loaded three high, with a clear space of 6 in between top and bottom of succeeding trays, on hand trucks built for the purpose. The loaded trucks were pulled into the freezing room where they remained for approximately 18 hr. The air temperature in the freezer was raised to about 10 F. when the trucks and concrete were brought in, but it was lowered to −10 F. in approximately 4 hr. and maintained at that point for the balance of the 18 hr. At the end of the freezing period the trucks were removed to the hallway and the specimens thawed at room temperature for approximately 6 hr. It was necessary to use a fan to blow the cold air away from around the bottoms of the trucks to get the lower trays to thaw out in about the same time as the upper trays. Trays were rotated in their positions on the trucks, and the several trucks rotated in their positions in the freezer and during thawing, so as to minimize the effects of variations between the different positions The specimens were left in the freezer during weekends and holidays. Freezing and thawing was discontinued on specimens representing a given nominal cement content and consistency of concrete until the reduction in sonic modulus for the group averaged approximately 30 percent. These specimens were then tested together with continuously moist cured companion specimens.

In making the transverse test the beam was placed on supports over a 16-in. span so that the finished surface would be in tension, and was loaded at the center. The ends broken off beams in the transverse tests were capped top and bottom with a 1:1 cement-sand mixture and tested in compression as modified cubes the following day. Load was applied to the top of the beam end as molded.

RESULTS

Because of more trial batches than anticipated it was necessary to replenish the supply of fly-ash. The second shipment was notably darker in color than the first, and analyses showed it to have approximately 13 percent more surface area and a little more than three times as much carbon. However, it was decided to use the fly-ash as received and observe any noticeable effects on the test results. Fly-ash from the second shipment was used in all the 2-in. and 6-in. slump concretes mixed on the third day and in the 6-bag, 6-in. slump concrete mixed on the second day. A review of the individual test results shows that in every case the concrete made using fly-ash from the second shipment had less air than concrete made using a like amount of fly-ash from the first shipment. This was particularly noticeable when the substitutions amounted to 25 and 35 percent.

The individual test results were subject to the usual wide dispersion from the averages, in a few instances in the very lean concrete as much as 100 percent. However, in the case of the modulus of rupture of moist cured concrete at least 85 percent of individual test results at each age were within 20 percent of the respective averages, and of frozen and thawed concrete at least 60 percent were within 20 percent of the averages. In the case of compressive strength the greatest deviation from the average was at the 3-day age when only 60 percent of individual results for the 2-in. slump concrete were within 20 percent of the average, but in all other instances, including frozen and thawed concrete, at least 85 percent of the individual compressive strength results at each age were within 20 percent of the respective averages Omission from the averages of test results outside the 20 percent limit would change some of the average values, but it would not change the over-all picture Therefore, except for a few instances with 3-bag concrete where specimen injury was indicated, no results were omitted because of deviation from the average.

A summary of averages of data pertaining to the mixes and of test results obtained on the fresh concrete of both consistencies is given in Table 4 The relationships between substitutions of fly-ash and cement content,

The air content of a given concrete was decreased as the substitution of fly-ash for cement was increased Richer nominal mixes in general contained less air than the leaner mixes.

It seems that within the range of mixes included in this test, the relations between fly-ash substitutions and cement content, water-cement ratio and air-content are substantially straight-line relationships

TABLE 4
DATA PERTAINING TO MIXES AND FRESH CONCRETE

	Nominal Cement Content (Bags per Cubic Yard)											
	3				4½				6			
	Fly-Ash Substitution (%)				Fly-Ash Substitutions (%)				Fly-Ash Substitutions (%)			
	0	15	25	35	0	15	25	35	0	15	25	35
	2-in Slump Concrete											
Mix Proportions by Weight	1 4 97 7 93				1 3 16 5 15				1 2 14 3 64			
Actual Cement, bags per cu yd	2 77	2 39	2 19	1 88	4 22	3 62	3 23	2 82	5 91	5 02	4 39	3 88
Fly-Ash, lb per cu yd	0	39 6	67 0	94 9	0	60 0	101 2	142 6	0	83 4	139 0	196 5
Water, gal per cu yd	28 2	27 1	26 3	25 8	28 2	27 4	26 9	26 1	30 5	30 1	29 7	29 4
W/C, by vol	1 36	1 51	1 64	1 83	0 89	1 01	1 11	1 23	0 69	0 80	0 89	1 00
Slump, in	2½	2¼	1¾	2	2	2	2½	2¼	2	2¼	2¼	2½
Air Content, %	7 1	6 0	5 0	4 5	5 6	5 0	4 4	3 8	3 6	3 5	3 1	2 5
	6-in Slump Concrete											
Mix Proportions by Weight	1 5 36 7 54				1 3 41 4 91				1 2 31 3 46			
Actual Cement, bags per cu yd	2 70	2 32	2 08	1 82	4 09	3 54	3 14	2 78	5 68	4 95	4 37	3 83
Fly-Ash, lb per cu yd	0	38 1	65 2	92 4	0	58 8	98 5	140 8	0	82 2	136 5	194 0
Water, gal per cu yd	31 6	30 0	29 9	29 3	30 9	29 9	29 5	28 4	32 9	31 8	32 4	30 6
W/C, by vol	1 56	1 72	1 91	2 14	1 00	1 12	1 25	1 36	0 77	0 85	0 99	1 07
Slump, in	6	6¼	5¾	5¾	5½	6¼	6¼	6¼	5½	5½	6¼	6
Air Content, %	7 4	7 0	5 7	5 0	6 8	5 7	5 2	3 9	5 7	4 0	3 4	3 0

water-cement ratio and air content are shown graphically for the 2-in. and 6-in slump concretes in Figures 1 and 2 respectively. These figures also show the relationships between substitutions of fly-ash and certain strength ratios which will be discussed later.

In all cases the substitution of fly-ash for cement resulted in only a small reduction in the amount of water required in the concrete to maintain a given consistency. The amount of cement being decreased by the exact amount that the fly-ash was increased, the net result was an increase in the water-cement ratio

The strengths of the concretes at the several test ages and after freezing and thawing, and certain strength ratios of the concretes of 2-in. slump are given in Table 5 and of 6-in. slump in Table 6. The strengths are shown graphically for the 2-in. and for the 6-in. slump concretes in Figures 3 and 4 respectively. There was a tendency for the transverse strength or modulus of rupture of the concrete under standard curing conditions to be slightly lower at 3 and 7 days, with increased substitutions of fly-ash At 28 days, however, the strength of concrete with fly-ash appeared to

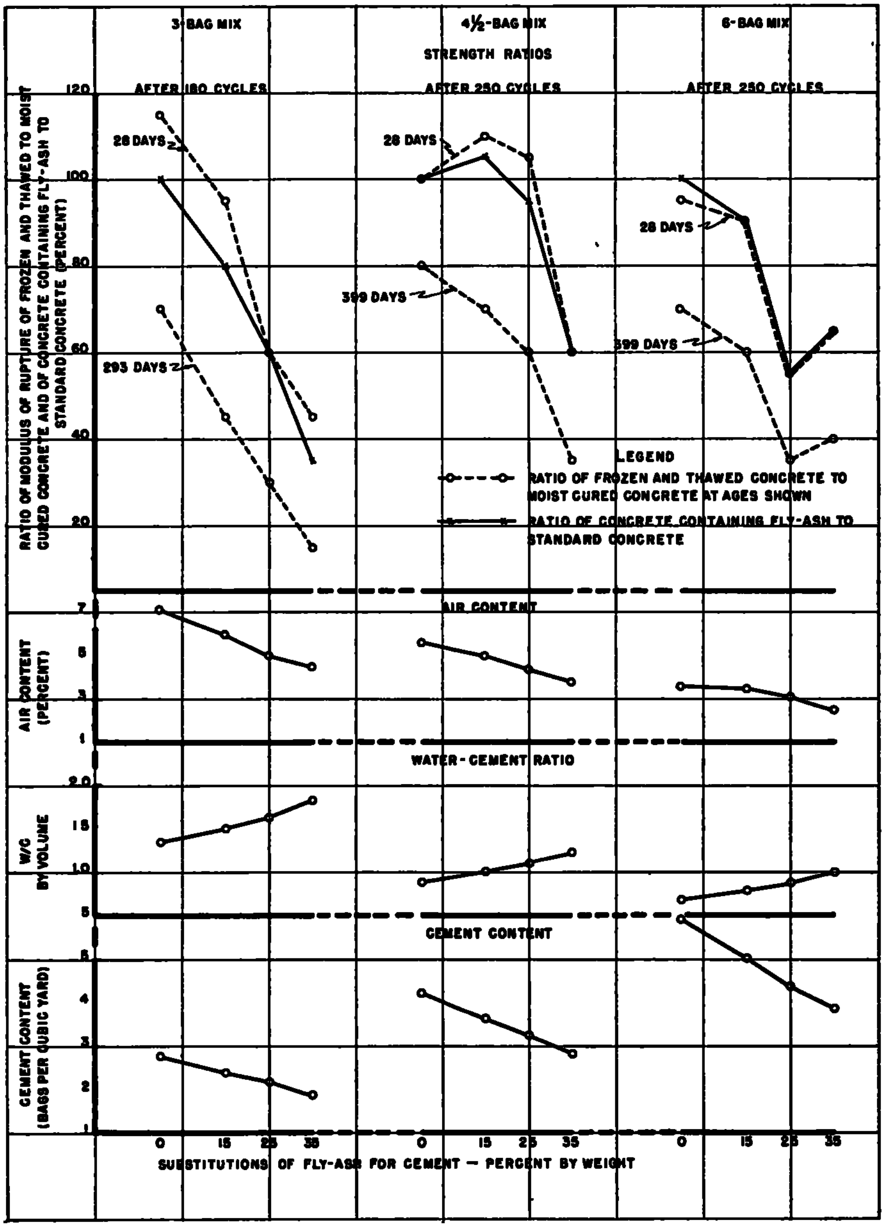

Figure 1. Cement Content, Water-Cement Ratio, Air Content and Resistance to Freezing and Thawing of Six-Inch Slump Concrete Containing Fly-Ash

be gaining and in some instances was equal to or greater than that of concrete having the full amount of cement At subsequent ages, varying from 130 to 400 days, the strengths of concretes with the greater substitutions of fly-ash had increased so that in several instances the concrete with the greatest substitution of fly-ash had the greatest strength. The data indicates that there may be an optimum substitution of fly-ash, as far as strength

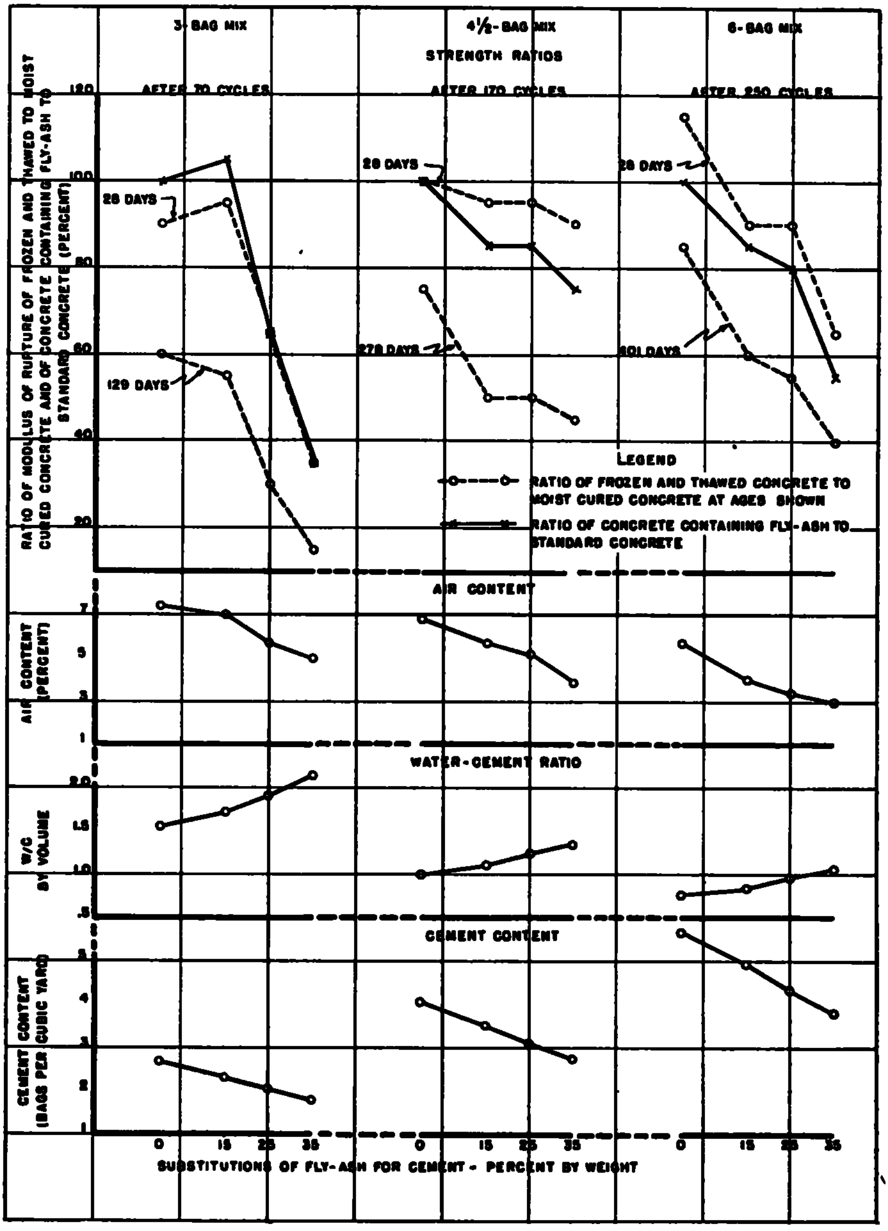

Figure 2. Cement Content, Water-Cement Ratio, Air Content and Resistance to Freezing and Thawing of Six-Inch Slump Concrete Containing Fly-Ash

alone is concerned, somewhere between 25 and 35 percent

After freezing and thawing, however, the strength of the concrete was generally decreased as the substitution of fly-ash was increased There were two exceptions, both in concrete having the 15 percent substitution of fly-ash. It appears that the modulus of rupture after freezing and thawing of the 6-bag, 2-in. slump concrete with the 25 percent substitution of fly-ash is out of line with the other values. The reason is not known and the point was ignored in drawing the strength curve in Figure 3.

The compressive strength test results showed the same general picture as did the transverse test results. However, the effects of substitutions of fly-ash on resistance to freezing and thawing did not appear to be so pronounced. This is in accord with the usual experience that the modulus of rupture is a more sensitive "indicator" of damage to the concrete than is compressive strength.

The ratio of the strength of frozen and thawed concrete to the strength of continuously moist cured concrete at the same age, and at 28 days, and the ratio of the strength of frozen and thawed concrete containing fly-ash to the strength of frozen and thawed concrete containing the full amount of cement (standard) are shown graphically for the 2-in. and 6-in. slump concretes in the upper parts of Figures 1 and 2 respectively.

TABLE 5

SUMMARY OF STRENGTH DATA FOR TWO-INCH SLUMP CONCRETE

		Nominal Cement Content (Bags per Cubic Yard)											
		3				4½				6			
		Fly-Ash Substitutions (%)				Fly-Ash Substitutions (%)				Fly-Ash Substitutions (%)			
		0	15	25	35	0	15	25	35	0	15	25	35
		Modulus of Rupture											
1	Moist Cured 3 Days	110[b]	145	115[b]	130[b]	300	295	285	230[b]	485	360	390	360
2	" " 7 Days	205[b]	190	160[b]	165[b]	415	395	355	330[b]	530	525	435	510
4	" " 28 Days	295	290	345	270	605	575	525	550	725	675	675	645
3	" " as indicated	293 Days				399 Days				399 Days			
		470	620	625[b]	715	755	885	960[b]	990	1000	1000	1060	1050
5	After Freezing & Thawing (Same total age as 4)	180 Cycles				250 Cycles				250 Cycles			
		340	280	200	120	595	630	560	345	690	610	370	435
6	Ratio 5 3, %	115	95	60	45	100	110	105	60	95	90	55	65
7	Ratio 5 4, %	70	45	30	15	80	70	60	35	70	60	35	40
8	Ratio of Str of Conc with Fly-Ash to Std [a], %	100	80	60	35	100	105	95	60	100	90	55	65
		Compressive Strengths—Modified Cube Test (psi)											
1	Moist Cured 4 Days	640	660	550	540	1550	1490	1400	1220	2310	2260	2200	1890
2	" " 8 Days	950[b]	820[b]	560[b]	650[b]	1840	1900	1720	1560[b]	3470	2930	2800	2500
3	" " 29 Days	1490	1550	1570	1540	3370	3290	2960	2840	5350	4700	4380	4400
4	" " as Indicated	294 Days				400 Days				400 Days			
		2210	2870	3160	3370	4450	5000	5340	5560	6400	6770	6820	6520
5	After Freezing & Thawing (Same total age as 4)	180 Cycles				250 Cycles				250 Cycles			
		2020	2080	1990	1700[b]	4200	4200	3870	3650	5960	5440	5320	4080
6	Ratio 5 3, %	140	140	130	110	130	130	130	130	110	120	120	90
7	Ratio 5 4, %	90	70	60	50	90	80	70	70	90	80	80	60
8	Ratio of Str of Conc with Fly-Ash to Std [a], %	100	100	100	80	100	100	90	90	100	90	90	70

[a] "Standard" refers to concrete with full amount of cement.
[b] These values are averages of two individual tests.

Considering the 2-in. slump concrete, the modulus of rupture after freezing and thawing was generally lower than that of continuously moist-cured concrete at 28 days. There were three exceptions, the 3-bag concrete with the full amount of cement and the 4½-bag concrete with 15 and 25 percent substitutions of fly-ash. Compared with concrete continuously moist cured for the entire period the modulus of rupture of frozen and thawed there was a decrease with each increase in the fly-ash substitution.

Considering the 6-in. slump concrete, the modulus of rupture after freezing and thawing with but one exception—the 6-bag concrete

TABLE 6
SUMMARY OF STRENGTH DATA FOR SIX INCH SLUMP CONCRETE

		Nominal Cement Content (Bags per Cubic Yard)											
		3				4½				6			
		Fly-Ash Substitutions (%)				Fly-Ash Substitutions (%)				Fly-Ash Substitutions (%)			
		0	15	25	35	0	15	25	35	0	15	25	35
		Modulus of Rupture											
1	Moist Cured 3 Days	110	105	110[b]	95	235[b]	205	190	180	365	325	325	275
2	" " 7 Days	175	160	150	120[b]	340	265	280	240	500	495	415	395
3	" " 28 Days	245	250[b]	215[b]	215	480	430	435	425	615	660	620	615
4	" " as indicated	129 Days				278 Days				401 Days			
		360	405	445[b]	450	665	850	870	820	855	990	1040	1035
5	After Freezing & Thawing (Same total age as 4)	70 Cycles				170 Cycles				250 Cycles			
		220	230[c]	135[b]	75	485	415	420	375[b]	710	600	565	395
6	Ratio 5 3, %	90	95	65	35	100	95	95	90	115	90	90	65
7	Ratio 5 4, %	60	55	30	15	75	50	50	45	85	60	55	40
8	Ratio of Str of Conc with Fly-Ash to Std [a], %	100	105	65	35	100	85	85	75	100	85	80	55
		Compressive Strengths—Modified Cube Test (psi)											
1	Moist Cured 4 Days	640	490	390[b]	410	1060	760	1040	800	1530	1540	1330	1290
2	" " 8 Days	770[b]	710[b]	560	600	1610	1230	1260	1100[b]	2400	2550	2000	2020
3	" " 29 Days	1050[b]	1060[b]	920	870	2690	2500	2240	2160	4120	4010	3350	3400
4	" " as indicated	130 Days				279 Days				402 Days			
		1600	1870	1950	2170	3450	3520	4300	3630	5170	6790	5880	6520
5	After Freezing & Thawing (Same total age as 4)	70 Cycles				170 Cycles				250 Cycles			
		1380	1260	1370[b]	1210[b]	3180	2810	2740	2380[b]	4920	4980	4580	4370
6	Ratio 5 3, %	130	120	150	140	120	110	120	110	120	120	140	120
7	Ratio 5 4, %	90	70	70	60	90	80	60	70	100	70	80	70
8	Ratio of Str of Conc with Fly-Ash to Std [a], %	100	90	100	90	100	90	90	80	100	100	90	90

[a] "Standard" refers to concrete with full amount of cement
[b] These values are averages of two individual tests
[c] These values represent one test only

concrete was substantially lower in all cases, and the difference was increased with each increase in the fly-ash substitution. Comparing the modulus of rupture after freezing and thawing of concrete containing fly-ash with that of concrete containing the full amount of cement with but one exception—the 4½-bag concrete with a 15 percent substitution—with the full amount of cement—again was generally lower than that of moist cured concrete at 28 days. Compared with concrete continuously moist cured for the entire period the modulus of rupture of frozen and thawed concrete was substantially lower in all cases, and the difference again was increased with each increase in the fly-ash substitution. Com-

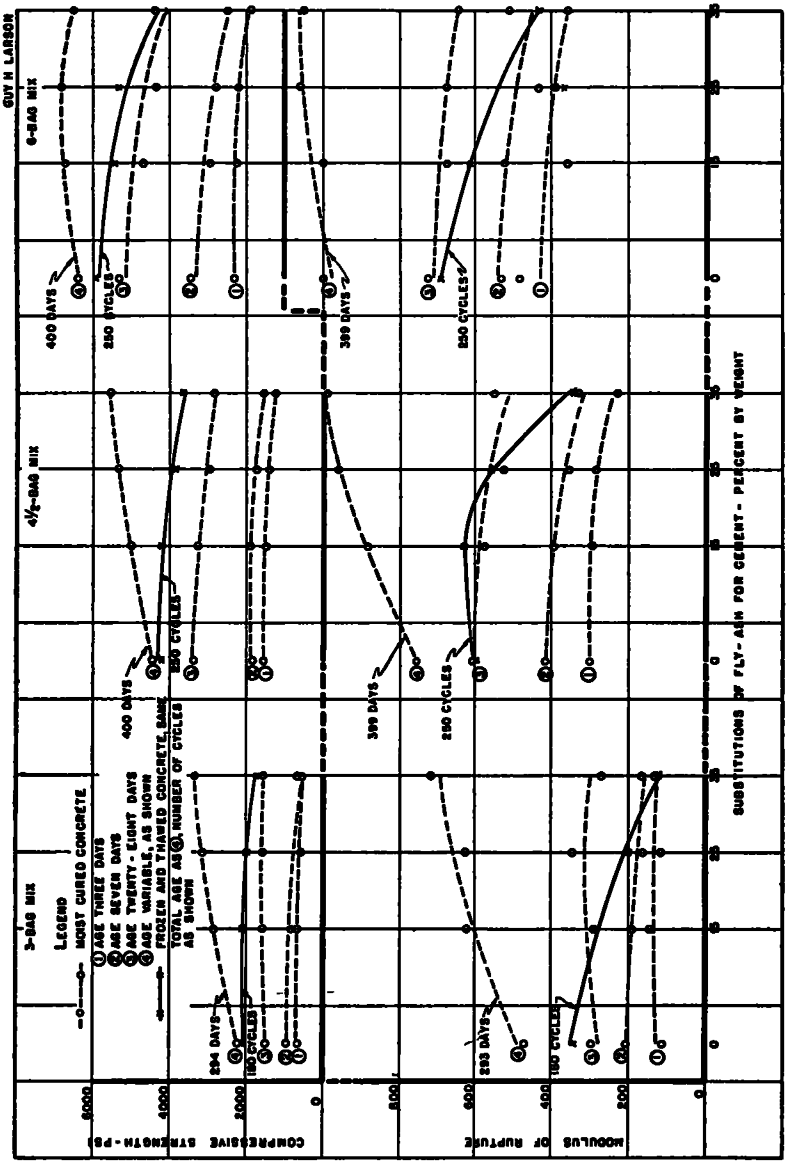

Figure 3. Modulus of Rupture and Compressive Strength of Two-Inch Slump Concrete Containing Fly-Ash

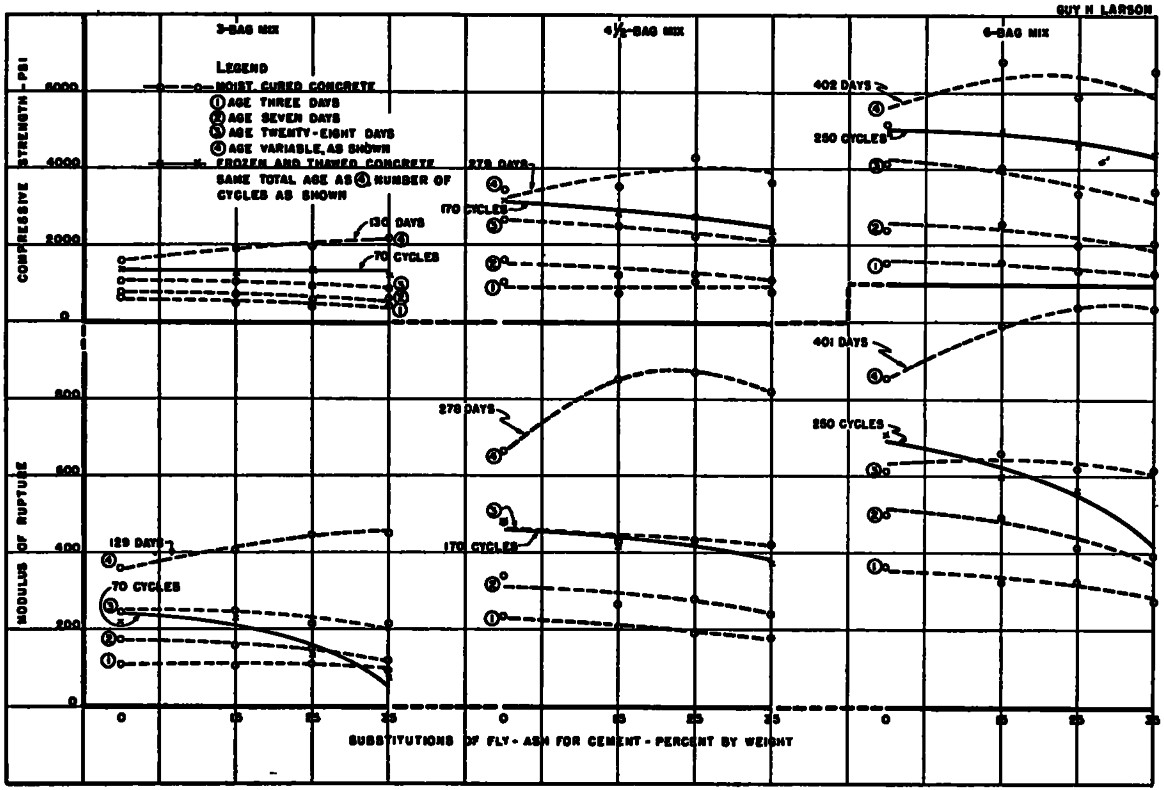

Figure 4. Modulus of Rupture and Compressive Strength of Six-Inch Slump Concrete Containing Fly-Ash

paring frozen and thawed concrete containing fly-ash with concrete containing the full amount of cement, with but one exception—the 3-bag concrete with a 15 percent substitution of fly-ash—the modulus of rupture of the concrete again was decreased with each increase in the fly-ash substitution.

Viewing the data as a whole in the light of established principles pertaining to concrete, it appears that fly-ash has a beneficial chemical action tending to improve the strength of concrete. The decrease in cement content and increase in water-cement ratio that accompanied substitutions of fly-ash for cement would normally tend to decrease the strength under standard conditions of curing, while the decrease in air content or increase in density would tend to increase strength. It is doubtful, however, that the beneficial effect of the increased density alone would be sufficient to counteract the adverse effects of decreased cement and increased water-cement ratio, and increase the strength to the extent that took place in this test. The decreased cement and air contents and the increased water-cement ratio would all normally tend to decrease the resistance of the concrete to freezing and thawing. It appears that their combined effect was sufficient to overcome the increased cementing value of the cement-fly-ash combination and resulted in a progressively lower strength after freezing and thawing as the fly-ash substitution was increased.

SUMMARY

The effects of increasing substitutions of fly-ash for cement in air-entrained concrete, as indicated within the limits and conditions of this test, were to:

1. Increase the water-cement ratio.
2. Decrease the air content.
3. Increase the strength of moist cured concrete at ages beyond 28 days, with substitutions of fly-ash up to 25 percent. There appears to be an optimum substitution, as far as strength is concerned, somewhere around 25 to 35 percent.
4. Increase the loss in strength due to freezing and thawing.

At the time this test was planned and started we did not know that the fly-ash would decrease the air content as it did, so the question of using additional air-entraining agent to bring the air content back up to that of the concrete without fly-ash was not covered. A series of tests has been started subsequently to determine the effect of such additional air-entraining agent on strength and durability, and we expect to have some information on that point at a later date.