HIGHWAY RESEARCH RECORD

Number 73

Symposium on Fly Ash in Concrete

5 Reports

Presented at the
43rd ANNUAL MEETING
January 13-17, 1964

HIGHWAY RESEARCH BOARD
of the
Division of Engineering and Industrial Research
National Academy of Sciences—
National Research Council
Washington, D. C.
1965

Department of Materials and Construction

John H. Swanberg, Chairman
Chief Engineer, Minnesota Department of Highways, St. Paul

CONCRETE DIVISION

Bryant Mather, Chairman
Engineer, Concrete Division, Waterways Experiment Station
Jackson, Mississippi

H. H. McLean, Vice Chairman
Director, Materials Laboratory
New York State Department of Public Works, Albany

COMMITTEE ON CHEMICAL ADDITIONS AND ADMIXTURES FOR CONCRETE

(As of December 31, 1963)

D. L. Bloem, Chairman
Director of Engineering, National Ready-Mixed Concrete Association
Washington, D. C.

H. Bobbitt Aikin, Senior Regional Engineer, Calcium Chloride Association, Washington, D. C.

Frederick E. Behn, First Assistant Engineer of Research, Ohio Department of Highways, Columbus

W. L. Dolch, Joint Highway Research Project, Purdue University, Lafayette, Indiana

H. C. Fischer, Chief, Concrete Specialties Section, Johns-Manville Products Corporation, Research Center, Manville, New Jersey

Bruce E. Foster, Chief, Inorganic Building Materials Section, National Bureau of Standards, Washington, D. C.

William E. Grieb, Physical Research Branch, U. S. Bureau of Public Roads, Washington, D. C.

Bryant Mather, Engineer, Concrete Division, Waterways Experiment Station, Jackson, Mississippi

Richard C. Mielenz, Director of Research, The Master Builders Company, Cleveland, Ohio

W. W. McLaughlin, Testing and Research Engineer, Michigan State Highway Department, Lansing

Harry H. McLean, Director, Materials Laboratory, New York State Department of Public Works, Albany

Howard Newlon, Jr., Virginia Council of Highway Investigation and Research, Charlottesville

M. E. Prior, Dewey and Almy Chemical Division of W. R. Grace and Company, Cambridge, Massachusetts

Raymond J. Schutz, Vice President, Research and Development, Sika Chemical Company, Passaic, New Jersey

Peter Smith, Senior Materials Engineer, Ontario Department of Highways, Toronto, Ontario, Canada

Rudolph C. Valore, Ridgewood, New Jersey

George J. Verbeck, Manager, Applied Research Section, Portland Cement Association, Skokie, Illinois

Contents

Experimental Fly Ash Concrete Pavement in Michigan

F. E. LEGG, Jr.
Associate Professor of Construction Materials, University of Michigan and
Materials Consultant, Michigan State Highway Department

An experimental fly ash concrete pavement, 1,750 ft long, was constructed in Michigan in 1955. Five sections are included in the project with ash contents varying from none to 200 lb/cu yd of concrete. Simultaneously, cement content was varied in increments from 5.5 to 4.0 sk/cu yd. Loss on ignition of the fly ash was high (13 to 14 percent), requiring very large amounts of air-entraining admixture to maintain the air content at levels considered necessary for satisfactory resistance to severe weather and deicing salts. Compressive and flexural strength test specimens were made from the job concrete from each section, and strengths are reported at ages up to 5 yr. Strengths of drilled cores are also reported along with accelerated scaling tests on job-made slabs. Observations at the age of 8 yr do not indicate positive superiority of behavior of any of the test sections and the present paper will have to be considered a combined construction and progress report.

•AS A PART of its research in the use of fly ash in portland cement concrete, the Detroit Edison Co. constructed an experimental highway pavement during the summer of 1955. The pavement is 1,750 ft long and is adjacent to the Edison Co. electrical generating power plant midway between St. Clair and Marine City, Mich.

During both the planning and construction stages of the road, the Michigan State Highway Department conducted preliminary laboratory investigations and field and laboratory tests, and furnished field engineering personnel and advice to the end that a maximum of information would be developed from the experimental project. During construction, the Engineering Research Institute of the University of Michigan assisted in performing field tests and conducted laboratory tests of samples collected at the construction site. The data presented herein are a composite of information gathered by these three agencies.

Insofar as applicable, the pavement was constructed in accordance with Michigan State Highway Department standards. The materials, with the exception of the fly ash, were tested by the Department before construction of the project. The fly ash was furnished by the Detroit Edison Co. from its St. Clair plant adjacent to the construction site. Tests of job samples of the fly ash showed it to have a loss of ignition of from 13 to 14 percent and a silicon dioxide content between 34 and 38 percent. The carbon content of this ash is thus higher than has been reported in the literature as having been used in a full-scale pavement and should make field observations of pavement performance of particular value. The silica content of the ash is also lower than is usually reported.

Numerous tests were conducted on the fresh concrete during the course of paving, and strength specimens were also secured for testing at ages up to 5 yr. Included were tests for air content, slump, and yield and molding of specimens to determine

---

Paper sponsored by Committee on Chemical Additions and Admixtures for Concrete.

the compressive strength, flexural strength, resistance to freezing and thawing, and resistance to salt scaling.

Concrete was also made in the laboratory subsequent to casting the pavement, using materials brought directly from the job. The same proportions were used in this concrete as for one of the test sections. The laboratory-made concrete gave slightly higher compressive and flexural strengths, even though a slightly higher water-cement ratio was used in the laboratory mixture.

LOCATION

The test pavement runs easterly along Recor Road from Mich. 29 about midway between St. Clair and Marine City, Mich. The main purpose of the road is to serve plant traffic of the St. Clair power plant of the Detroit Edison Co. This traffic consists of heavily loaded trucks hauling waste fly ash from the power plant and other services for the plant as well as some light local residential traffic. The grade is essentially level for the entire 1,750-ft length. The test road terminates at each end in right angle turns so that traffic is not high speed. Outbound heavily loaded trucks from the plant are confined to the westbound lane. All traffic traverses all five test sections because the single side entrance is a gravel road and is rarely used. Figure 1 gives the plan of the road and the test sections.

PAVEMENT STRUCTURE

The pavement is 22 ft wide, 8 in. thick, uniform, and reinforced throughout with welded wire mesh consisting of No. 00 longitudinal wires spaced at 6 in. and No. 4

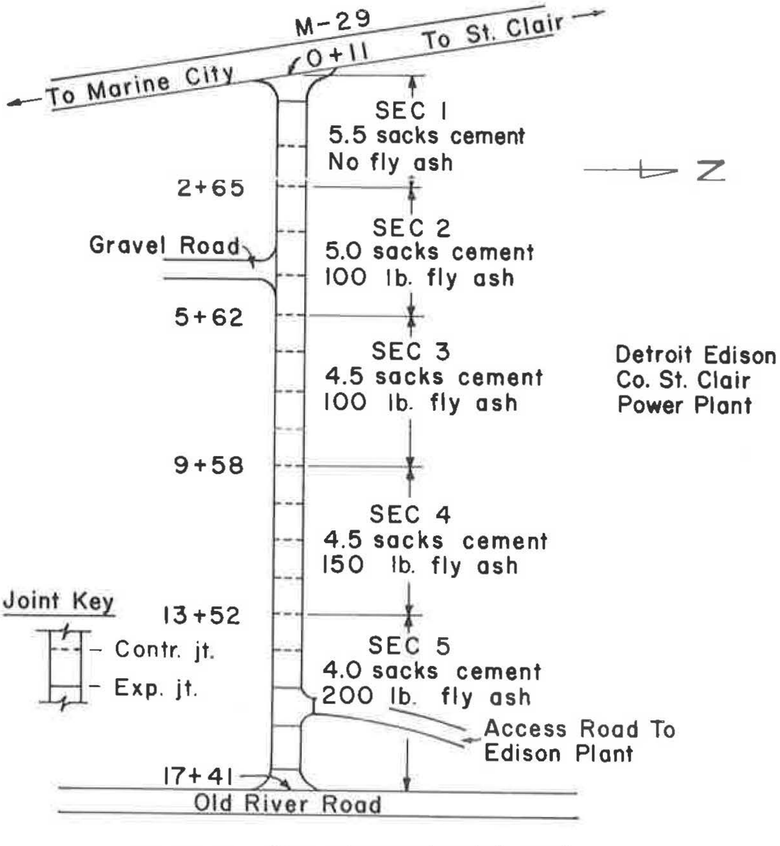

Figure 1. Plan of experimental road.

TABLE 1

TESTS OF SUBBASE AND SUBGRADE SOIL

Property	Station				
	2 + 25 R	5 + 25 R	8 + 50 R	11 + 25 R	14 + 25 L
(a) Subbase					
Depth of subbase (in.)	13	13	9	13	-
Passing sieve (%):					
1-in.	100	100	100	100	-
No. 40 sieve	97	95	96	93	-
No. 100 sieve	23.4	12.4	25.4	19.3	-
Loss by washing (%)	14.5	6.2	17.3	11.6	-
Density in place (Rainhart) (lb/cu ft)	115	116	112	115	-
moisture (%)	11.7	11.6	13.3	12.0	-
Field cone density (lb/cu ft)	118	-	-	-	-
moisture (%)	10.8	-	-	-	-
(b) Subgrade					
Composition (%):					
Coarse sand	4	3	1	2	1
Fine sand	20	17	12	22	14
Silt	37	38	37	37	36
Clay	39	42	50	39	49
Liquid limit	51	56	62	59	57
Plasticity index	28	32	36	33	33

transverse wires spaced at 12 in. Load transfer is accomplished at all transverse joints using 1-in. diameter steel dowels, spaced at 12 in. on center. The longitudinal center joint was sawed. All joints are sealed with hot poured rubber-asphalt filler. The subbase for the pavement consists of 9 to 13 in. of sand over the highly plastic natural clay soil. Table 1 gives tests of the sand subbase and subgrade.

PAVING EQUIPMENT

Paving was accomplished using one 34-E dual drum mixer. The concrete was initially leveled by a mechanical spreader after being dumped from the mixer bucket. Finishing was accomplished by a transverse finisher followed by a mechanical longitudinal float. Final finishing consisted of hand straightedging followed by

TABLE 2

TESTS OF PORTLAND CEMENT—JOB SAMPLES

Property	Date Sampled	
	7-7-55	7-8-55
Specific surface, air permeability test (sq cm/g)	3,455	3,221
Autoclave expansion (%)	0.09	0.12
Normal consistency (%)	24.4	24.4
Time of set, Gillmore (hr-min):		
Initial	3:05	3:00
Final	5:05	5:00
Compressive strength (psi):		
At 7 days	3,933	3,354
At 28 days	5,246	4,779
Mortar air content (%)	8.6	8.6
Chemical composition (%):		
SiO_2	20.1	20.1
Al_2O_3	6.3	6.0
Fe_2O_3	2.8	2.8
CaO	63.7	63.7
MgO	2.4	2.4
SO_3	2.7	2.4
Loss on ignition	1.5	1.4
Na_2O	0.27	0.29
K_2O	0.75	0.76
Total alkali as Na_2O	0.76	0.79
C_3S	52	55
C_2S	18	16
C_3A	12	11
C_4AF	9	9

TABLE 3

TESTS OF FLY ASH—JOB SAMPLES

(ASTM Method C 311-54T)

Property	Date Sampled	
	7-7-55	7-8-55
Specific surface, air permeability test (sq cm/g)	3,204	3,010
Compressive strength of mortar (% of control):		
At 7 days	173	160
At 28 days	147	167
At 90 days	161	171
Autoclave expansion (%)	0.04	0.04
Drying shrinkage of mortar (%)	0.10	0.11
Specific gravity	2.48	2.36
Chemical composition (% by dry wt):		
SiO_2	34.0	37.8
Al_2O_3	21.2	21.7
Fe_2O_3	25.2	25.9
MgO	0.8	1.0
SO_3	0.8	0.5
Loss on ignition	14.0	13.0
Moisture	0.4	0.3

a burlap drag to roughen the surface. White pigmented curing compound was applied by an automatic spraying machine also riding on the forms. The dry batch trucks were loaded at the batch plant in Marine City, about 4 mi south of the project, but the fly ash was introduced into the batch trucks from a raised platform at the job. The appropriate amount of fly ash for the particular batch was weighed into steel drums and dumped by hand into the trucks on top of the other dry ingredients. This was a dusty and undesirable method of batching the fly ash but was done in lieu of requiring a separate bin and weighing equipment for such a short project.

CONCRETE MATERIALS

Cement

Except for the first 34 batches in Test Section 1, the cement was Type I. The contractor had some Type IA remaining in his bin which was used in these first 34 batches. Tests on job samples of the Type I cement, used throughout the remainder of the project, are given in Table 2. It was desired to use Type I cement on the project to compare accurately the air-entraining admixture requirements for the various test sections.

TABLE 4

TESTS OF FINE AGGREGATE—JOB SAMPLES

Property	Date Sampled	
	7-7-55	7-8-55
Passing sieve (% by wt):		
⅜-in.	100	100
No. 4	97	96
No. 8	83	84
No. 16	66	66
No. 30	47	46
No. 50	20	17
No. 100	3.3	2.9
Loss by washing (%)	1.0	1.2
Specific gravity	2.64	2.64
Absorption (%)	1.11	1.27
Fineness modulus	2.85	2.89
Organic matter, plate no.	1	1

TABLE 5

TESTS OF COARSE AGGREGATE—JOB SAMPLES
(Crushed Limestone)

Property	Date Sampled			
	7-7-55	7-7-55	7-8-55	7-8-55
Size designation	4A	10A	4A	10A
Passing sieve (% by wt):				
2-in.	100	-	100	-
1½-in.	90	100	96	100
1-in.	32	99	38	99
½-in.	6	60	8	43
⅜- in.	4.1	-	4.9	-
No. 4	-	6.9	-	3.8
Loss by washing (%)	1.2	1.5	1.3	1.0
Soft or nondurable particles (%)	0.1	0.6	0.0	0.3
Chert particles (%)	0.0	0.0	0.0	0.0
Hard absorbent particles (%)	0.0	0.0	2.7	0.9
Thin or elongated particles (%)	0.0	1.8	0.0	2.3
Specific gravity	2.78	2.78	2.79	2.78
Absorption (%)	0.54	0.74	0.51	0.64

Fly Ash

Job samples of the fly ash were obtained on two different days; test results using ASTM Method C 311-54T are given in Table 3. It will be noted that the two samples had 13.0 and 14.0 percent loss on ignition, respectively. This high loss results from the fact that the St. Clair power plant was just undergoing initial trials and combustion was not yet favorable.

Fine Aggregate

The fine aggregate was a local natural sand displaying no unusual characteristics. Analyses of job samples using applicable ASTM methods are given in Table 4.

Coarse Aggregate

The coarse aggregate was a crushed dolomite considered to have excellent durability characteristics. The stone was furnished in two sizes, 2- to 1-in. nominal, and 1-in. to No. 4 sieve. Equal amounts of the two sizes, by weight, were used in all the test sections. Analyses of job samples using applicable ASTM methods are given in Table 5.

Air-Entraining Admixture

Neutralized Vinsol resin dissolved in water at the rate of 50 lb of Vinsol NVX to 50 gal of water was used throughout. This solution was prepared in advance and stored in drums along the roadway.

CONCRETE MIXTURE PROPORTIONS

Standard Michigan State Highway Department practice is to provide 5.5 sk of cement per cubic yard and, in 1955, entrained air in the amount of 3 to 6 percent. As a consequence, it was decided to use this same concrete mixture in the first test section to provide a basis for comparison with those sections containing fly ash. The choice of cement content and fly ash for the fly ash sections was arbitrary with previous laboratory work having indicated the probability of not much loss of later strength with the chosen combinations of amounts of fly ash and cement. The amounts of fly ash used in each test section are given in Table 6. As indicated in the table, the coarse aggregate content was raised slightly accompanying the increase of fly ash. Previous experience indicated that the added plasticity of the fresh concrete afforded by the fly ash allowed greater stone contents without loss of workability.

SAMPLING AND TESTING PROCEDURES

The procedures used in sampling and testing the fresh concrete, concrete materials, and hardened concrete generally followed Michigan State Highway Department practices, which are based on ASTM methods.

Field tests on the fresh concrete consisted of the following:

1. Air test: Using a pressure air meter, tests were made about every hour after the proper amount of air-entraining admixture was determined for each section. To fill the air meter bowl, the samples of concrete were taken from three successive batches, whenever possible, to average out minor variations between batches.
2. Slump test: An average of three slump tests were made in each section. More frequent tests seemed unnecessary because it was possible to detect from the appearance of the fresh concrete if substantial change in slump occurred.
3. Kelly ball penetrations: Kelly ball tests were occasionally made during casting of the first three test sections.
4. Weight per cubic foot determinations: These determinations were made at one point in each test section. The calibrated measure was filled and weighed three times for each test to provide a reliable average.
5. Temperature of the fresh concrete was observed once or twice in each test section. The temperature remained quite steady, ranging from 82 to 89 F with little regard for variations in air temperature.

Samples of the fresh concrete were cast into cylinders, slabs, beams, and bars for testing at later ages. Two groups of 6- by 12-in. cylinders were cast for compression testing. Group A consisted of three cylinders for each age of 1, 3, 7, 28, and 90 days and 1 and 5 yr. These cylinders were cast in waxed cardboard molds with metal bottoms. The 1-day cylinders were returned to the laboratory in time to be broken 24 hr after molding. The other Group A cylinders were returned to the laboratory 2 or 3 days after molding and were placed in the moist-fog room for curing until the time for testing. Group B consisted of four cylinders for each age of 1, 7, 28, and 90 days and 1 yr. These cylinders were cast in disposable sheet metal molds and the top surface was sprayed with white curing compound 1 to 2 hr after casting. The 1-day cylinders from this series were similarly taken to the laboratory for testing 24 hr after casting. The cylinders for testing at later ages were taken to the laboratory after approximately 4 days. They were air cured, protected by the metal mold and curing compound, until time for testing. The third set of compression specimens was designated Group C and consisted of cores, drilled the full depth of the pavement, approximately 5.9 in. in diameter. Three cores were drilled from each section approximately 2 wk ahead of time and stored in 70 F lime water until tested. The rough subgrade ends were sawed off and both ends were capped with sulfur compound before placing in the testing machine. Cores were drilled for testing at ages of 28 and 90 days and for 1 and 5 yr.

TABLE 6

MIX PROPORTIONS

Test Section	Portland Cement (sk/cu yd)	Fly Ash (lb/cu yd)	Vol Loose Coarse Agg.[a]
1	5.5	0	0.78
2	5.0	100	0.83
3	4.5	100	0.83
4	4.5	150	0.85
5	4.0	200	0.85

[a] Per vol of concrete.

Fourteen beams, 6- by 6- by 36-in., were made from each section, furnishing two beams for testing in flexure at each age of 1, 3, 7, 28, and 90 days and 1 and 5 yr. Two flexure breaks, using center point loading, were obtained from each beam, giving four values for the flexural strength in each section for each age. The steel molds were stripped from the beams the morning after casting. No effort was made immediately to protect the concrete from the sun and wind. The beams for testing at 1 and 3 days of age were tested with a portable breaker in the field. The beams for testing at ages of 7, 28, and 90 days were taken to the laboratory about 5 days after casting and were stored in the moist-fog room until time for testing. The beams for testing at 1 and 5 yr were buried with the top face flush with the ground surface adjacent to the pavement site. Approximately 3 wk before testing, the latter beams were brought to the laboratory and placed in the moist room until broken. Due to a misunderstanding at the job site, the 5-yr specimens were removed from the earth in the fall of 1959 and subsequently stored in outdoor air but were similarly conditioned in the moist room before testing.

Three freeze-thaw bars, 3- by 4- by 16-in., were cast from each section. This concrete was wet screened before molding bars to eliminate all coarse aggregate retained on a 1-in. sieve. As with the larger beams, these bars were unprotected from the weather until taken to the laboratory about 3 days after casting and were moist cured from that time until the freezing and thawing started.

Two small slabs with a 16- by 24-in. top surface and integral curbs about 1 in. high were made for each section. These slabs were used to study the resistance to scaling due to application of sodium chloride for ice removal. The top surface of the slabs were sprayed with curing compound shortly after molding. About 5 days after molding, they were buried with the top surface flush with the ground adjacent to the pavement site. Four months later the slabs were brought to the laboratory for scaling tests. One slab from each section was frozen to 0 F once daily with a 4 percent solution of sodium chloride ponded on the surface. The other slab was frozen outdoors by natural weathering, similarly ponded for the first two years.

In all cases, the concrete for the test specimens was obtained toward the end of each test section. In Section 1, the concrete was obtained by the shovelful just after it was deposited by the mixer on the subgrade. This involved carrying the concrete across a ditch to get to the point where the specimens were fabricated. Because of the large amount of concrete required for the numerous samples, about $\frac{3}{4}$ cu yd, the concrete for the specimens in the remaining sections was deposited directly from the mixer bucket immediately adjacent to the molds. In this way all concrete for the Group A cylinders came from one batch, all concrete for the Group B cylinders and the slabs came from another batch, and all concrete for the beams and bars came from still another batch. This permits the possibility of differences due to variations between batches, instead of providing an average by taking the concrete from several batches as was done in the first section.

TEST RESULTS

Table 7 gives the mix proportions and Tables 8 and 9 give strength results of the job concrete.

Strength Tests

Major interest centers around the strength behavior of the five test sections as a clue to predicting ultimate pavement performance. In the case of flexural strength, only one set of test specimens is available and, therefore, conclusions regarding flexural strength will have to rest on this one set of data. Figure 2 is a plot of the gain in flexural strength over 5 yr. It is observed that the ranking of the test sections changes somewhat according to the age of observation. At 5 yr, all sections have flexural strengths exceeding 900 psi.

In the case of compressive strength, the three sets of specimens give somewhat different results and different ranking of the test sections at different ages. Subjective decisions may favor one or the other sets of compression specimens as more reliable

TABLE 7

MIX PROPORTIONS OF JOB CONCRETE

Test Section	Cement (sk/cu yd)	Fly Ash (lb/cu yd)	Sand (lb/cu yd)	Stone (lb/cu yd)	Avg Net Water (lb/cu yd)	Avg W/C (gal/sk)	Wt of Fresh Concrete (lb/cu ft)	Avg Air Content (%)	Vinsol (avg lb/cu yd)	Slump (in.)	Kelly Ball Pen. (in.)
1	5.52	0	1,218	2,060	231	5.0	150.8	5.0	0.078	2¾	2¾
2	5.01	100	1,008	2,195	239	5.7	150.0	4.5	0.442	3	1½
3	4.48	100	1,022	2,196	227	6.1	147.1	6.1	0.447	2½	1½
4	4.54	150	925	2,250	242	6.5	150.1	5.1	0.539	3¼	-
5	4.05	200	918	2,250	240	7.2	150.0	5.0	0.892	2½	-

TABLE 8

COMPRESSIVE STRENGTH OF JOB CONCRETE

Test Section	Compressive Strength (psi)						
	1 Day	3 Days	7 Days	28 Days	90 Days	1 Yr	5 Yr
				(a) Group A—Cylinders			
1	1,590	2,500	3,070	3,590	4,380	5,445	6,920
2	1,200	2,040	2,590	3,400	4,220	5,005	5,980
3	1,155	1,800	2,170	2,750	3,500	4,110	5,050
4	1,115	2,020	2,500	3,400	4,245	4,740	5,800
5	1,250	1,780	2,200	3,150	3,920	4,575	5,750
				(b) Group B—Cylinders			
1	1,995	-	3,500	4,235	4,685	5,400	-
2	1,430	-	3,240	4,000	4,785	5,560	-
3	1,540	-	2,880	3,720	4,105	4,680	-
4	1,030	-	2,615	3,460	4,040	4,730	-
5	1,440	-	2,890	3,940	4,760	5,355	-
				(c) Group C—Cores			
1	-	-	-	4,775	5,580	5,560	6,440
2	-	-	-	4,340	4,550	5,270	6,580
3	-	-	-	3,580	4,125	4,030	5,770
4	-	-	-	4,340	5,400	5,500	6,170
5	-	-	-	4,015	4,715	5,415	6,310

TABLE 9

FLEXURAL STRENGTH OF JOB CONCRETE

Test Section	Flexural Strength (psi)						
	1 Day	3 Days	7 Days	28 Days	90 Days	1 Yr	5 Yr
1	370	399	577	606	707	894	1,185
2	269	403	542	634	786	919	1,135
3	370	399	509	640	737	842	970
4	269	405	548	682	845	924	980
5	277	355	408	533	635	787	915

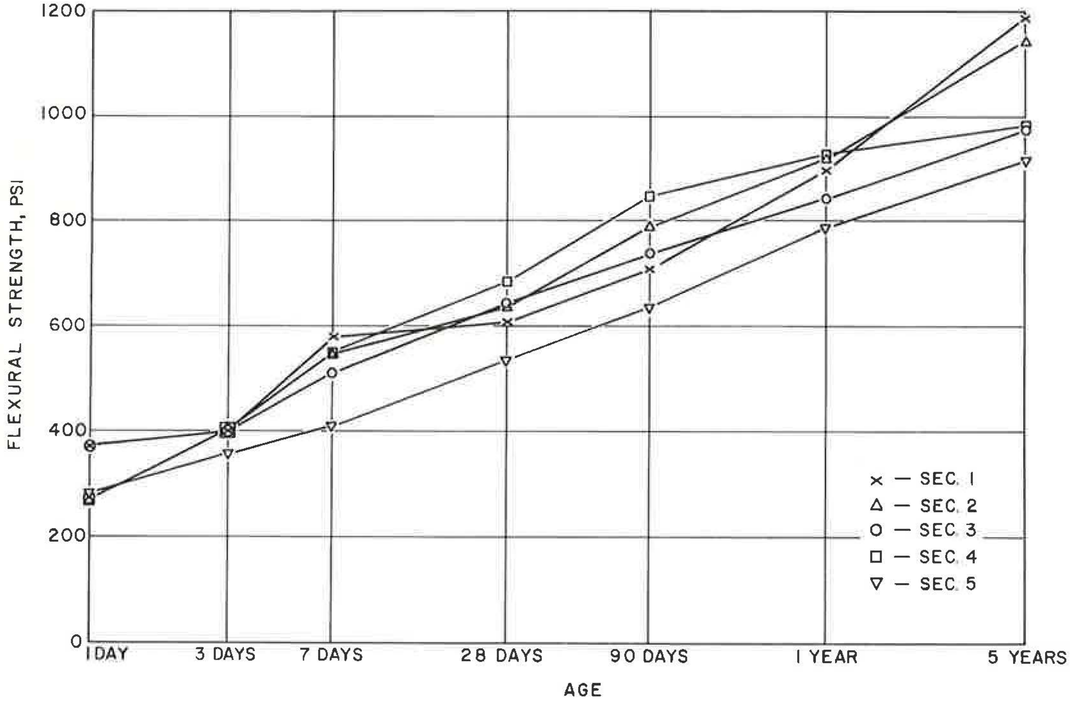

Figure 2. Flexural strength of beams.

or as more valid for comparison purposes. An overall index of compressive strength, possibly more objective, may be obtained by averaging all three types of specimens where available (i. e., drilled cores, laboratory-cured cylinders, and special cylinders cast in metal molds), giving each type equal weight in the average. Such an average is plotted in Figure 3. On the basis of this index, Section 1 without fly ash exhibits slight advantage at all ages and Section 3 is lowest except at an age of 1 day. The other three sections are intermediate and practically indistinguishable as to strength properties.

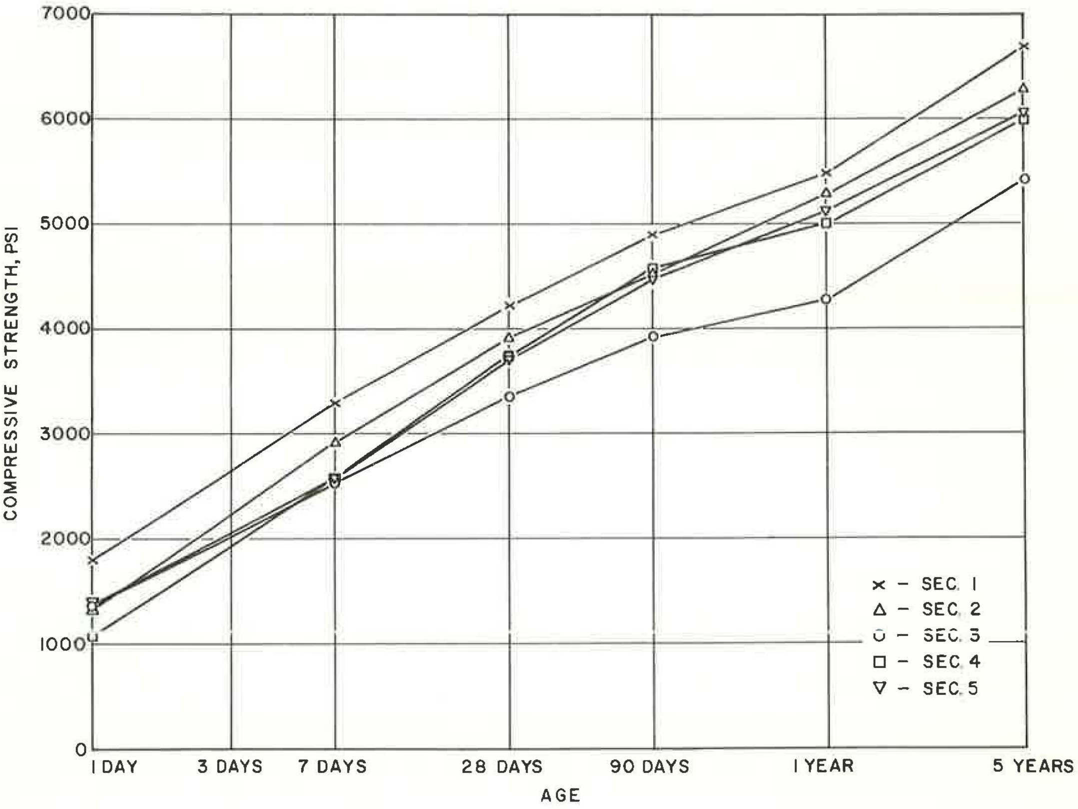

Figure 3. Composite compressive strength of all specimens.

TABLE 10

FREEZE-THAW RESULTS

Section	No. Cycles for Failure			
	Bar 1	Bar 2	Bar 3	Average
1	899	445	800	715
2	122	82	107	104
3	142	246	160	183
4	118	335	184	212
5	349	347	98	265

TABLE 11

RATINGS OF SCALING SLABS

Cycles	Section				
	1	2	3	4	5
10	0	1	0	2	0
50	0	1	0	2	0
100	0	1	0	2	1
150	0	1	1	3	2

Freezing and Thawing

Two of the 3- by 4- by 16-in. bars from each section were placed in the automatic freeze-thaw unit after moist curing 4 mo. One additional bar from each section was placed in freezing and thawing at the age of 5 mo, when additional space became available. Six cycles were obtained daily with the specimens submerged in water in close-fitting stainless steel containers using ASTM Method C 290. Air at 0 F was used as the freezing medium and water at 40 F was used for thawing. When the sonic modulus had dropped to 70 percent of the initial value, the beam was considered to have failed. Table 10 gives the number of cycles for failure.

Observations of the pavement at 8 yr of age do not permit confirmation of the apparent ranking indicated by the freeze-thaw tests. There is presently no evidence of deterioration. Possibly the actual pavement which was placed on a well-drained base has never reached the moisture content induced by the complete submergence used in the accelerated laboratory tests and has, therefore, never become vulnerable to freeze-thaw attack.

Surface Scaling Tests

Small slabs from each test section were subjected to freezing and thawing with a 4 percent solution of sodium chloride ponded on the top surface to determine relative resistance of the various sections to scaling due to application of deicing salts. A small amount of scaling was induced on most of the slabs in the artificial exposure in the laboratory and no scaling on the slabs in the natural exposure outdoors. Most of the scaling on the slabs in the laboratory occurred in the first 10 cycles and is believed due to overfinishing and to popouts of small shale particles in the sand.

Table 11 gives the ratings of each of the slabs in the accelerated laboratory exposure. They were rated by visual examination on a scale of from 0 to 10. The rating scale is:

0 = no scale,
1 = scattered spots of very light scale,
2 = scattered spots of light scale,
3 = light scale over about one-half the surface,
⋮
10 = deep scale over entire surface.

Despite the acknowledged severity of the laboratory scaling treatment, resistance to scaling was excellent to good for all test sections. Companion specimens stored outdoors and ponded with chloride solution for the first two years show no evidence of scaling up to the present time. In the intervening years, the surface of the latter specimens change moisture content because of falling snow and rain and summer evaporation.

COMPARISON OF FIELD AND LABORATORY CONCRETE

It was contemplated that useful information might be derived by making concrete in the laboratory using job materials so as to develop confidence in future prediction from laboratory tests. The validity of laboratory tests with respect to job-manufactured concrete is often questioned. Samples of stone, sand, cement, and fly ash used on the experimental project were obtained directly from the batch plant bins on the job for use on concrete to be made, cured, and tested in the laboratory. These were used in the same proportions as in Section 4 of the road project. Two 6- by 12-in. cylinders for compression testing at 1, 7, 28, and 90 days and one 6- by 6- by 36-in. beam for flexural testing at 7, 28, and 90 days were made from each of three batches, providing six cylinders and three beams for each age.

The concrete was mixed in a mixer with rotating paddles on a horizontal shaft using a 2-min initial mix followed by a 2-min rest period with mixer stopped, followed by a 3-min final mixing. Results of the laboratory tests are shown in Table 12, together with comparable data from the field concrete.

TABLE 12

COMPARISON OF LABORATORY AND FIELD MIXED CONCRETE—TEST SECTION 4

Property	Laboratory	Field
Cement (sk/cu yd)	4.56	4.54
Fly ash (lb/cu yd)	150	150
Material proportions (lb/cu yd)		
Sand	913	925
Stone	2,250	2,250
Net water	269	242
Water-cement ratio (gal/sk)	7.2	6.5
Wt of fresh concrete (lb/cu ft)	151.5	150.1
Air content (%)	4.6	5.1
Slump (in.)	2	3.25
Compressive strength (psi)		
1 day	1,300	1,070[a]
7 days	2,810	2,560[a]
28 days	3,910	3,730[a]
90 days	4,880	4,560[a]
Flexural strength (psi)		
7 days	540	548
28 days	790	682
90 days	890	845

[a] Composite of all specimens.

TABLE 13

VINSOL RESIN REQUIRED IN EACH TEST SECTION

Section	Vinsol Resin	
	Lb/Cu Yd	Amount Relative to Section 1 (times)
1	0.078	1.0
2	0.442	5.7
3	0.447	5.7
4	0.539	6.9
5	0.892	11.4

It is observed from the tabulation that strengths of the laboratory concrete are comparable to those of the field concrete except for flexural strength at 28 days. In the latter case, only, substantially greater strengths were observed for the laboratory concrete.

PAVING OPERATIONS AND AIR-ENTRAINING ADMIXTURE REQUIREMENTS

In addition to procuring the numerous test specimens during the paving operation, various supplemental observations were made. Air temperatures, for instance, were unusually high for the area, averaging about 88 F and reaching as high as 97 F. Fresh concrete temperatures stayed within the range of 82 to 89 F.

The method of batching the fly ash slowed operations considerably, particularly for Sections 4 and 5, thus causing an intermittent flow of batch trucks to the mixer. This, in turn, caused variability of mixing time and interfered with the normal sequence of finishing operations.

To maintain proper air content, the Vinsol resin solution had to be batched by hand into the mixer skip because the amounts far exceeded the capacity of the automatic dispenser on the mixer. Table 13 gives the average amounts of admixture required in the five test sections. Severe fluctuations in air content occurred only in Section 5 (4 sk of cement and 200 lb of fly ash), and there was insufficient opportunity to trace the source of the difficulty. Measured air varied from 2 percent to 10 percent in Section 5.

Although partially anticipated when planning the project, actual experience on the job amply demonstrated that the individual test sections were too short to develop fully all information desired. The contractor provided the paving equipment, as requested, for a full-scale operation. Slowing down the operation to a 300- to 400-ft test section in a half day meant that the paving equipment itself was spread out over practically an entire test section. By the time progress had settled down on a given section, the necessary air and yield checks made and test specimens fabricated, the section was essentially completed. Practically no opportunity arose to experiment with finishing procedures. Appearance of the pavement after construction indicated that for the sections having greater fly ash contents, the burlap drag was applied too early to provide a properly roughened surface. The contractor's personnel were naturally acquainted with procedures where straight portland cement mixes are used which do stiffen earlier, particularly in the hot, dry weather prevalent at the time of construction. There was, therefore, an understandable tendency to finish the surface too early. This was particularly apparent for Section 5 having the lowest cement content and highest fly ash content.

EIGHT-YEAR FIELD PERFORMANCE OBSERVATIONS

Performance of the constructed road has been watched with interest, particularly to discern any differences in behavior of the five test sections. General appearance of the road at 8 yr of age is excellent. There is no evidence of scaling and only one slight corner break (at the joint terminating Section 3). Aggregate popouts are practically nonexistent. Slight evidence of surface abrasion from shoulder pebbles thrown on the pavement by sharp turning movements is apparent at both ends of the project in Sections 1 and 5.

Early in the spring of the year following construction, three longitudinal cracks appeared in Section 5, wandering as much as 3-ft from the sawed center joint. These cracks have a total length of about 85 ft and appear associated with the tendency of heavily loaded outbound trucks, when there is no oncoming traffic, to make a wide turn and straddle the centerline when leaving the power plant. Since that time, no additional longitudinal cracks have been observed. However, one transverse crack in Section 1 and two transverse cracks in Section 2 were observed at 5 yr. At 8 yr, one transverse crack and a short (3-ft) crack appeared in Section 3. Certainly the amount of cracking would be considered very minor for a Michigan pavement of this age.

SUMMARY

In 1955 a full-scale test pavement, 1,750 ft long, was constructed in Michigan containing four combinations of portland cement with a high-carbon fly ash. The fifth control section contained no fly ash and corresponded to 5.5 sk air-entrained concrete pavement normally used by the Michigan State Highway Department. Based on tests made on the job concrete during and subsequent to construction and on periodic examination during the 8 yr of service of the test road, the following observations are made:

1. A composite compressive strength index obtained by averaging the three types of compressive specimens utilized showed that four of the five test sections exceeded 3,500-psi strength at 28 days of age and were close to, or exceeded, 6,000-psi strength at 5 yr. Test Section 3 containing 4.5 sk of cement and 100 lb of fly ash per cubic yard was of somewhat lower compressive strength, although drilled cores showed that even this section satisfied a 3,500-psi requirement at 28 days.
2. At the earlier ages, flexural strengths of all sections, including the control section without fly ash, were lower than anticipated, possibly reflecting failure to moist cure the specimens properly at very early ages. However, by 90 days of age, four of the sections exceeded 700-psi flexural strength. Section 5, containing 4 sk of cement and 200 lb of fly ash per cubic yard, had a 90-day flexural strength of 635 psi with a 5-yr strength of 915 psi. The other sections all exceeded 950 psi at 5 yr.
3. In accelerating laboratory freeze-thaw and salt scaling tests of the job concrete, the concrete without fly ash displayed some superiority. However, it was one of the aims of the test road to develop a relation, if it existed, between accelerated laboratory tests and actual service performance. Examination of the test road at the age of 8 yr reveals no distress attributable to freezing and thawing or salt scaling. The latter is particularly significant because the road itself had been heavily salted with sodium chloride (rock salt) during the winter months to keep it free of ice and snow. Past observations of paving concrete in the Michigan area permit the prediction that lack of scaling in the first 8 yr makes it unlikely that vulnerability to salt attack will develop later.
4. Up to 11 times as much air-entraining admixture was used in one of the fly ash sections as in the control section to achieve the desired air content. It is admitted that severe fluctuations in air content, despite constant admixture dosage, occurred in this section (Section 5). However, in fly ash Section 4, seven times as much admixture was required and no particular control problems arose. This observation tends to substantiate the requirements of ASTM Specification Designation: C350, "Fly Ash for Use as an Admixture in Portland Cement Concrete," that large amounts of admixture may be used provided the particular admixture has no undesirable side effects when so used.

5. Earlier versions of ASTM C350 prescribed a 40 percent minimum silica content which the fly ash in the present case failed to meet. The propriety of a later version (ASTM C350-60T) seems confirmed, however, where the sum of silica, alumina, and iron oxide are required to total at least 70 percent. The sum of these three components for the fly ash in this test road amounted to 80 to 85 percent.

6. The high loss on ignition of the fly ash (13 to 14 percent) in the test road required large amounts of air-entraining admixture to compensate for the depressing effect on air, but the 8-yr service record of the pavement does not presently reflect adverse effects. Reexamination of the basis for a maximum limit of 12 percent loss appears indicated.

7. Observations at the age of 8 yr do not indicate positive superiority of behavior of any of the five test sections, and the present paper will have to be considered a combined construction and progress report.

ACKNOWLEDGMENTS

Appreciation is expressed for the help of many individuals who aided in planning and establishing the test program for this experimental road. Particular thanks are owed to the Detroit Edison Co. staff and to Ralph Vogler, then associated with the Engineering Research Institute of the University of Michigan, Ann Arbor. Members of the Cooke Contracting Co., Detroit, contractors for the test road, were most cooperative in every way.

Use of Fly Ash in Concrete Pavement Constructed in Nebraska

CHARLES A. SUTTON
Senior Engineer of Physical Tests, Nebraska Department of Roads

Nebraska has an abundance of sand-gravel in streams and old lake beds that in many ways is an excellent aggregate for use in concrete. It provides a concrete that is highly workable in the plastic stage and durable with high strength after it hardens. However, certain materials in this aggregate often react with portland cements in such a manner that disruptive expansion is produced in the concrete and its useful life is considerably reduced.

Various methods for inhibiting this reaction and its resulting expansion have been investigated and one method that showed considerable promise in a series of laboratory tests was the use of fly ash in the concrete. Because the laboratory tests were favorable, two experimental test roads, each approximately 6 mi in length, were constructed with concrete involving the use of fly ash. One road was constructed in 1950 and the other in 1951. Results indicate that the use of fly ash in the concrete presented no special problems in construction and the fly ash concrete was durable, high in strength and did not expand because of cement-aggregate reaction.

•CONSIDERABLE QUANTITIES of sand-gravel are available over most of Nebraska. This aggregate consists of angular to rounded pebbles of granite, quartz, and feldspar, with minor amounts of accessory minerals and metamorphic and sedimentary rocks. It occurs as alluvial deposits in modern and ancient stream beds or terraces; because it originates from weathered rock that has been subjected to the washing action of water, only the hardest and most durable particles remain. This excellent aggregate, when combined with the proper proportions of cement, air-entraining agent and water, produces a concrete that is both plastic and easy to handle before it hardens, and develops high strength and durability after it hardens. However, concrete made with Nebraska sand-gravel is subject to progressive and permanent expansion caused by a cement-aggregate reaction, which in some instances seriously damages the concrete within a few years.

Through field surveys and laboratory studies it has been determined that replacing 30 percent of the sand-gravel aggregate with crushed limestone will satisfactorily inhibit this reaction, and a concrete using substitutions of limestone has been in general use by the Nebraska Department of Roads since 1947. This has proven to be a sound and durable concrete in every respect, but because sources of good quality limestone are limited within the state, the Department is constantly looking for other means of inhibiting cement-aggregate reaction.

One method that appears to be particularly promising is the use of fly ash in the concrete. Tests conducted in the laboratory indicated that if 25 or 30 percent of the cement used in sand-gravel aggregate concrete is replaced with fly ash, serious ex-

---

Paper sponsored by Committee on Chemical Additions and Admixtures for Concrete.

pansion would not develop. Because the laboratory tests indicated a favorable reduction in expansion, two experimental paving test roads were constructed with concrete in which fly ash was used in varying amounts. This is a report of these field studies.

The special engineering required for these studies was furnished by the Materials and Tests Division of the Nebraska Department of Roads, in cooperation with the U. S. Bureau of Public Roads, using Highway Planning funds.

DESCRIPTION OF TEST ROADS

One of the test roads was constructed between Fremont and Arlington, Neb., on US 30 in August and September 1950. US 30 is one of the main traveled roads across Nebraska (Fig. 1). This 6.15-mi long project was chosen because it is a straight and level stretch of road with no heavily traveled intersecting highways and, therefore, should have a uniform traffic load throughout the length of the project. Bollen and Sutton have previously described the construction of this project and reported some of the early tests on the concrete (1). Throughout this report this test road is identified as the Fremont project.

Before 1947, the Nebraska Department of Roads used two different classes of concrete (Classes A and H) for most concrete construction. Both used a sand-gravel aggregate, but the aggregate for Class H concrete was coarser on the coarse fraction of the aggregate and also finer on the fine fraction than the aggregate for Class A concrete. The aggregate for Class H concrete had approximately 26 percent retained on the No. 4 sieve and 21 percent passing the No. 30 sieve, whereas the aggregate for Class A concrete had only 19 percent retained on the No. 4 sieve and 13 percent passing the No. 30 sieve.

TABLE 1

QUANTITIES OF MATERIALS PER CUBIC YARD OF CONCRETE
(Fremont Project)

Class of Concrete	Cement (sk)	Fly Ash (lb)	Total Aggregate (tons)	Air Content (%)	Aggregate
47B	6.0	None	1.45-1.55	4-7	30% Crushed limestone[a] 70% Sand-gravel[a]
A	7.0	None	1.32-1.47	5-9	100% Sand-gravel[b]
A1	6.0	94	1.32-1.46	5-9	100% Sand-gravel[b]
A2	5.0	188	1.30-1.45	5-9	100% Sand-gravel[b]
A + 2	5.5	188	1.28-1.43	5-9	100% Sand-gravel[b]
H	6.4	None	1.41-1.53	4-8	100% Sand-gravel[c]
H1	5.4	94	1.40-1.52	4-8	100% Sand-gravel[c]
H2	4.4	188	1.39-1.51	4-8	100% Sand-gravel[c]

[a] Crushed limestone—approximately 18 percent retained on $^3/_4$-in. sieve, 95 percent retained on No. 4; sand-gravel—15 percent retained on No. 4 sieve, 18 percent passing No. 30 sieve.

[b] Sand-gravel—approximately 19 percent retained on No. 4 sieve, 13 percent passing No. 30 sieve.

[c] Combined sand-gravel aggregate—approximately 26 percent retained on No. 4 sieve, 21 percent passing No. 30 sieve.

Because most sand-gravel aggregate sources in Nebraska are deficient in coarse material, the aggregate for Class H concrete was more difficult to produce. However, because it had more coarse material, only 6.4 sk of cement were used per cubic yard of concrete, whereas 7 sk per cubic yard were used in the Class A concrete.

After it was discovered that concrete made with Nebraska sand-gravel aggregates is subject to progressive expansion and that substitutions of a good quality of crushed limestone for part of the sand-gravel aggregate would inhibit this expansion, the sand-gravel types of concrete were abandoned in favor of one using crushed limestone. This concrete was identified as Class 47B, and since 1947 most of the concrete for the Nebraska Department of Roads has been of this type.

All three of these classes of concrete were used on the Fremont project along with three combinations of Class A and two combinations of Class H concrete in which part of the cement was replaced with fly ash. The proportions and basic quantities of materials per cubic yard are given in Table 1. Classes 47B, A and H are the standards for comparisons; A1, A2, A + 2, H1 and H2 were included to show the effect of fly ash on sand-gravel aggregate concretes.

Test sections of pavement were constructed with each class of concrete in combination with each of two brands of Type I portland cement, making a total of 16 different combinations. Four sections were repeated, making a total of 20 sections involved in this study of fly ash. Six other sections were constructed, but because they are not pertinent to this report, they are not discussed.

The contract for this project required that the length of repetitive sections be from 600 to 1,400 ft and that of other sections from 1,000 to 1,800 ft. The contractor was free to choose any sequence in the use of the different classes of concrete and brands of cement except that he was required to have at least two sections of other classes of concrete separating sections having the same composition and proportions.

The other test road is located between Laurel and Belden, Neb., on US 20 in the northeast part of the state. This road is approximately 5.9 mi in length and is referred to in this report as the Laurel project. It was constructed in September and October 1951. The terrain in this area is gently rolling with good drainage and the soil varies from loess to a sandy loam with some areas of almost pure dune sand. US 20 is a main traveled highway extending east and west across the northern part of the state. A considerable amount of farm stock is trucked over this road enroute to the market at Sioux City, Iowa. The location of this project is also shown in Figure 1.

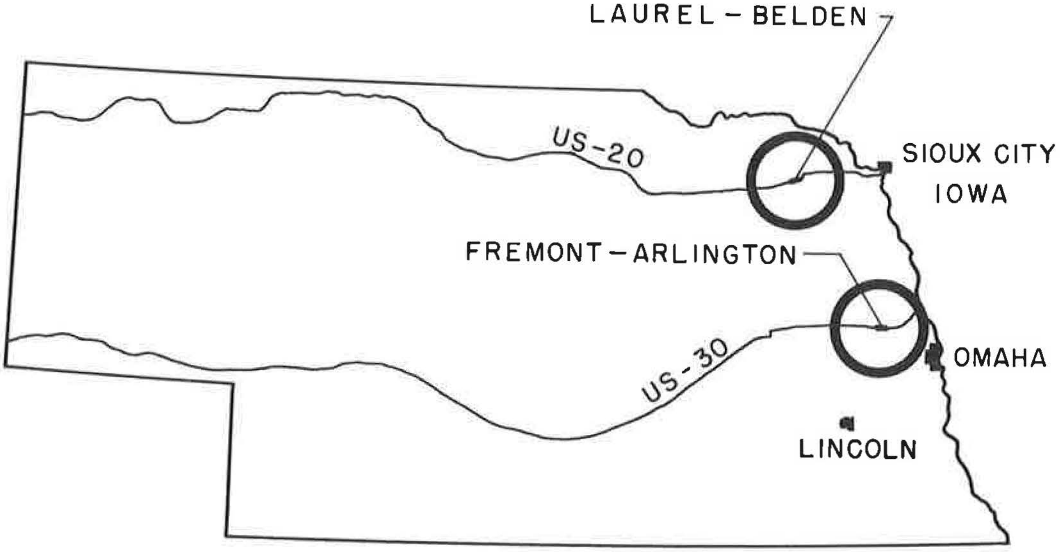

Figure 1. Location of Nebraska test roads.

The contract for construction of this project required that 10 to 15 percent of the area of the concrete pavement should be constructed with regular Class A concrete and the remaining 85 to 90 percent should be constructed with a corresponding concrete in which 25 percent of the cement had been replaced with fly ash. The contract also required that one brand of cement be used throughout the project. The mixture proportions for each class of concrete are given in Table 2.

Both projects have many things in common in their design. The concrete pavement was 22 ft wide, with a uniform thickness of 8 in., and was laid directly on 4 in. of compacted granular foundation course. Contraction joints were spaced at 16-ft 4-in. intervals throughout both projects. Expansion joints were provided only on bridge approaches and where the new pavement joined old existing concrete. Tie bars were placed across the centerline joint and load transfers were used in the few expansion joints. No load transfers were provided at the contraction joints and no reinforcing mesh was used in the slab. Both projects were approximately 6 mi in length and were constructed during the latter part of the summer.

The sand-gravel for both projects was obtained from a wet pit on the Platte River near Fremont, Neb., and the crushed limestone for the Fremont Project came from a quarry near Weeping Water, Neb. Each car of cement used on both projects was sampled and tested for physical characteristics and some samples were also tested to determine their chemical composition. The minimum and maximum values of these tests are given in Table 3 for each brand of cement. The fly ash for both projects was supplied by the Chicago Fly Ash Co. of Chicago, Ill. Each car was sampled and tested, and the results of these tests are given in Table 4.

PAVING OPERATIONS

The materials were dry batched to a 34-E paving mixer at the paving site. The paving operations were similar to those used on other projects except that a hopper was required to weigh the fly ash. However, no extra operations were required in the production of fly ash concrete because during the time that a hopper was used to weigh fly ash, a hopper for weighing crushed limestone was not required. Therefore, one simply took the place of the other.

Because of the fineness and peculiar flowing characteristics of fly ash, small holes and cracks in the truck boxes that normally could hold cement had to be plugged. The leakage was most noticeable at the point of loading, and when a truck box was made tight enough to hold fly ash while it was being loaded, no leakage occurred enroute to the project. Close inspection of the loading and hauling of fly ash was especially necessary during the first few trips. Although the fly ash was the last material to be placed in the cement compartment of the truck and was not covered with canvas, very little blew off the truck during the trip to the project. The fly ash lost much of its flowing and dusting characteristics after it had settled in place in the truck.

TABLE 2

QUANTITIES OF MATERIALS PER CUBIC YARD OF CONCRETE
(Laurel Project)

Class of Concrete	Cement (sk)	Fly Ash (lb)	Aggregate (tons)	Air Content (%)	Aggregate[a]
A	7.0	None	1.32-1.47	5-9	100% Sand-gravel
A1.75	5.25	165	1.30-1.45	5-9	100% Sand-gravel

[a] Sand-gravel—approximately 19 percent retained on No. 4 sieve, 13 percent passing No. 30 sieve; Class A is standard 100 percent sand-gravel aggregate concrete used also on Fremont project.

TABLE 3

ANALYSIS OF CEMENT
(Fremont and Laurel Projects)

Property	Brand A, Type I		Brand B, Type I	
	Min	Max	Min	Max
Mortar air content (%)	3.4	11.9	5.0	12.1
Specific surface (sq cm/g)	1,653	1,974	1,854	2,104
Soundness:				
Steam Chest	OK	OK	OK	OK
Autoclave expansion (%)	0.091	0.224	0.054	0.154
Time of set, Gillmore (min)				
Initial	2:00	3:20	2:05	3:15
Final	3:20	4:45	3:30	4:35
Tensile strength (psi)				
At 3 days	290	368	265	373
At 7 days	370	440	368	467
At 28 days	450	523	447	543
Compressive strength (psi)				
At 3 days	1,483	2,191	1,366	2,275
At 7 days	2,516	2,800	2,125	3,350
At 28 days	4,266	5,008	3,483	4,166
Chemical composition (%)				
SiO_2	21.6	23.0	21.6	22.5
Al_2O_3	4.9	6.0	3.6	4.9
Fe_2O_3	2.6	3.1	2.7	3.3
CaO	62.6	65.2	61.8	63.2
MgO	0.4	0.7	3.5	4.8
SO_3	1.6	2.0	1.6	2.0
Loss on ignition	0.9	1.8	1.1	1.6
Insoluble residue	0.19	0.40	0.31	0.69
$3CaO \cdot SiO_2$	34	57	40	54
$2CaO \cdot SiO_2$	19	39	22	34
$3CaO \cdot Al_2O_3$	8	11	4	8
Na_2O	0.25	0.33	0.14	0.18
K_2O	0.43	0.55	0.45	0.53
Total alkali, $Na_2O + K_2O$	0.68	0.83	0.59	0.69
Equivalent alkali, $Na_2O + 0.658 \times K_2O$	0.53	0.66	0.44	0.51
Water-soluble alkali	0.04	0.07	0.18	0.25
P_2O_5	0.04	0.18	Trace	0.03
Mn_2O_3	0.15	0.18	0.06	0.09
Chloroform-soluble organic substances	Trace	0.005	Trace	0.002
CaO	0.6	2.1	0.2	0.3
Al_2O_3: Fe_2O_3	1.6	2.2	1.1	1.8

There was nothing unusual about the paving train or the paving operations. Each batch was mixed for a minimum time of 1 min. An air-entraining agent was added to the mix by an automatic dispenser on the mixer. All pavement was cured with kraft paper, which was left on for a minimum of 4 days.

Control of the paving operations was maintained by performing yield, slump, and air-content tests at least every 150 lin ft throughout the Fremont project and at frequent intervals on the Laurel project. A special effort was made to keep the air content of the concrete near the upper limit of the specifications. The additional control tests performed were not as a result of any difficulties encountered but merely as a means of insuring good quality concrete.

CHARACTERISTICS OF PLASTIC CONCRETE

The behavior of the fly ash concrete mixed in the field was similar to that made in the laboratory. For a given air content and slump, the use of fly ash caused a reduction in the required amount of mixing water and increased the plasticity of the mix.

All test sections (with or without fly ash) were constructed with air-entrained concrete. It was noticed that when a higher-carbon fly ash was used in the mixtures, two or three times more air-entraining agent was required for a given air content than when a lower-carbon fly ash was used.

TABLE 4

ANALYSIS OF FLY ASH
(Fremont and Laurel Projects)

Property	Min	Max
Specific gravity	2.44	2.59
Fineness:		
Retained on No. 325 sieve (%)	3.4	8.7
Specific surface:		
Wagner	1,334	2,286
Blaine	3,143	4,878
Pozzolanic activity 7 day compressive strength (psi)[a]	848	1,210
Chemical composition (%):		
SiO_2	42.8	50.5
Al_2O_3	14.4	18.5
MgO	0.4	0.7
SO_3	1.6	3.5
Ignition	0.7	3.3
Free carbon	0.6	2.6

[a] Compressive strength of 2- by 4-in. cylinder composed of 2 parts fly ash, 1 part hydrated lime, 9 parts standard Ottawa sand and water to produce a workable mix; cylinders cured in sealed containers at 70 F for 24 hr and 130 F for 6 days.

The rounded particles of Nebraska sand-gravels contribute to a highly workable concrete with a low water-cement ratio. This factor combined with the water-reducing characteristics of air entrainment results in concrete that requires only 31 to 35 gal of mixing water per cubic yard. Concrete with such a low water requirement may be very plastic and easy to work during periods of normal temperatures and humidity but because very little bleeding water is available, the surface of the concrete will dry rapidly and become rubbery and difficult to finish during periods of high temperature and low humidity.

Although the average slump was increased approximately $\frac{3}{4}$ in. for the sections using fly ash, less mixing water was used in these sections and they seemed to bleed even less than the other sections. Most of the concrete made with fly ash was more workable and finished more easily than corresponding non-fly ash concrete, but difficulty with finishing did develop in some localized areas of sections using fly ash during periods of high temperature and low humidity. The difficulties were not serious, and because of the many variables that affect finishing on a field project—variations not only in the weather but also in the construction procedures and in the materials themselves—it was impossible to trace the difficulty directly to the use of fly ash. Under similar conditions it is possible that all classes of concrete used on the project would have been difficult to finish.

SPECIAL TEST AREAS

Special test areas were chosen within the longer sections of pavement representing each class of concrete. Concrete cylinders and beams for laboratory tests were molded during placement of concrete in these areas. Usually the test specimens were fabricated from the concrete at two different locations within each section but in some instances where the sections were short, all specimens were fabricated at one location. Enough specimens were cast to provide at least two for each type of test and test period. The concrete for the specimens was loaded directly from the mixer into a truck and then hauled to a convenient site where the specimens were cast.

STRENGTH TESTS

All specimens fabricated for strength tests were cured under damp burlap for the first day, in damp sand for the next 4 days, and then in a moist closet until they were tested for strength. The unit compressive strengths of 6- by 12-in. cylinders representing each class of concrete are shown in Figure 2. With few exceptions the strength increased with age, and whatever retrogressions did occur probably resulted from variations in test methods rather than from actual variations in strength.

The concrete fabricated with 100 percent sand-gravel aggregate and no fly ash (Classes A and H) had compressive strengths from 5,800 to slightly over 7,000 psi at 540 days age. In most instances the concrete in which fly ash was used to replace part of the cement (A1, A2, A + 2, A1.75, H1 and H2) had slightly lower early compressive strengths but at later ages the strengths were higher than similar concrete without the substitution of fly ash. The strength of concrete using 188 lb of fly ash and brand B cement was approximately 15 percent higher at 540 days age than that of similar concrete without fly ash (A2 and A, H2 and H). All concretes using 188 lb of fly ash per

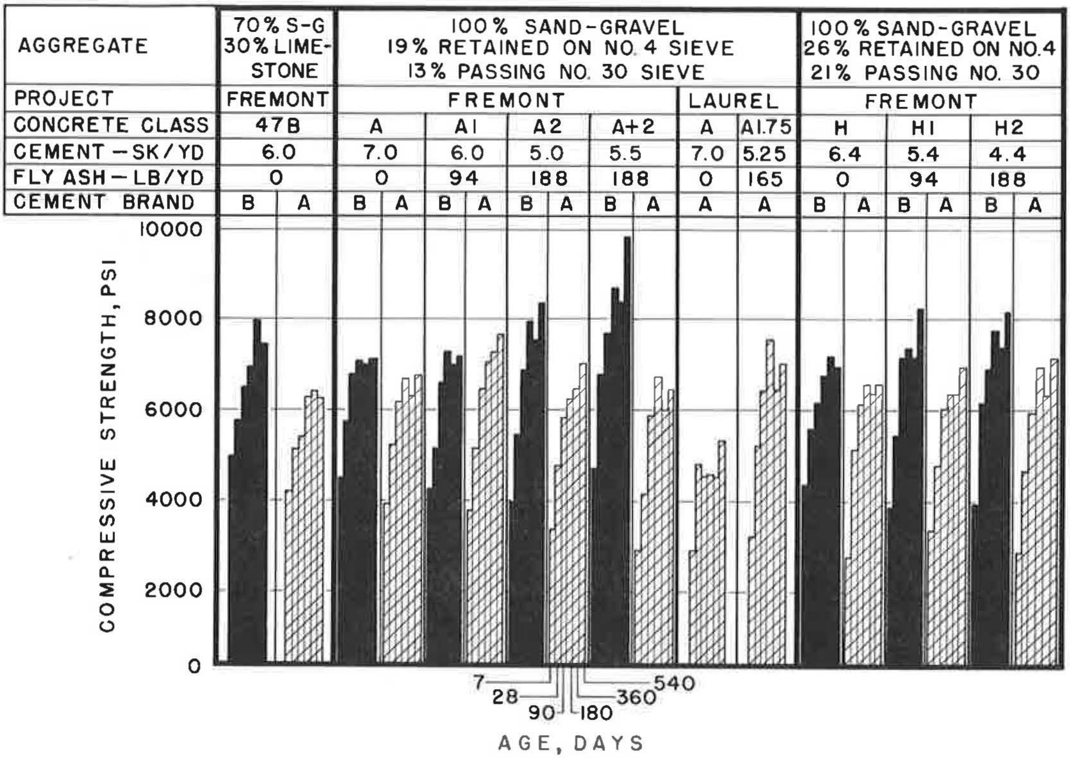

Figure 2. Compressive strength of concrete cylinders.

cubic yard had strengths at later ages that were equal to or slightly higher than the strength of Class 47B concrete made with the same brand of cement. Of all the different types of concrete, the highest compressive strength developed in concrete cylinders using 100 percent sand-gravel aggregate, 5.5 sk of brand B cement and 188 lb of fly ash per cubic yard of concrete (A + 2). At 540 days, the strengths of these cylinders averaged nearly 10,000 psi.

Concrete beams (6- by 6- by 30-in.) were cast from each class of concrete and tested for flexural strength. These tests are shown in Figure 3. The flexural strengths had the same trends as the compressive strengths except that the gain in ultimate strength when fly ash was used in concrete made with brand A cement was more pronounced. Here again the early strengths of concrete made with fly ash were slightly lower than similar concrete without fly ash, but the ultimate strengths were higher. The flexural strength of Class A + 2 concrete made with brand B cement tested higher (1,500 psi) than any concrete ever tested in this laboratory and considerably higher than the average for concrete from field projects. All classes of concrete using fly ash had higher ultimate flexural strengths than Class 47B concrete made with the same brand of cement.

Considering all the various classes of concrete, the flexural and compressive strengths were above the average obtained on most pavement projects in Nebraska, and in some cases the ultimate strengths were considerably above average.

DURABILITY TESTS

Beams, 3- by 4- by 16-in. in size, were fabricated from each class of concrete for weathering tests. These beams were cast with a stainless steel plug in each end so that their change in length could be measured with a comparator. They were cured

7 days in a moist condition, 21 days in laboratory air and 2 days in water. After curing, the beams were distributed to various weathering exposures and tested for sonic modulus of elasticity or measured for change in length at various ages.

Wetting and Drying Exposure

Some beams respresenting each class of concrete were allocated to a wetting-and-drying exposure in which they were subjected to repeated cycles of 9-hr immersion in 65 ± 5 F water and 15 hr in circulating air at 120 F. The beams were measured periodically for change in length and sonic modulus. During 1 yr of this exposure, beams fabricated with cements and aggregates that are known to have a poor service record and are considered reactive expand 0.050 percent or more and crack in various degrees of disintegration.

The percent change in length of the beams exposed to wetting and drying are shown in Figure 4. Beams respresenting concrete made with 30 percent limestone sweetening (Class 47B) expanded only a moderate amount during this exposure. This further substantiates previous tests and pavement condition surveys indicating that sweetening with 30 percent crushed limestone will inhibit destructive cement-aggregate reaction in concrete made with Nebraska sand-gravel.

The beams representing concrete made without crushed limestone or fly ash (Classes A and H) expanded considerably more than any of the other sets of beams. Beams fabricated with Class A concrete using brand B cement and with Class H using either brand B or brand A cement expanded more than 0.050 percent during 1 yr of exposure. Beams from the Fremont project representing Class A concrete made with brand A cement expanded only 0.025 percent at 12 mo of exposure, but at 18 mo their expansion was 0.067 percent which was approximately equal to the expansion during the same amount of time of corresponding concrete made with brand B cement. Beams

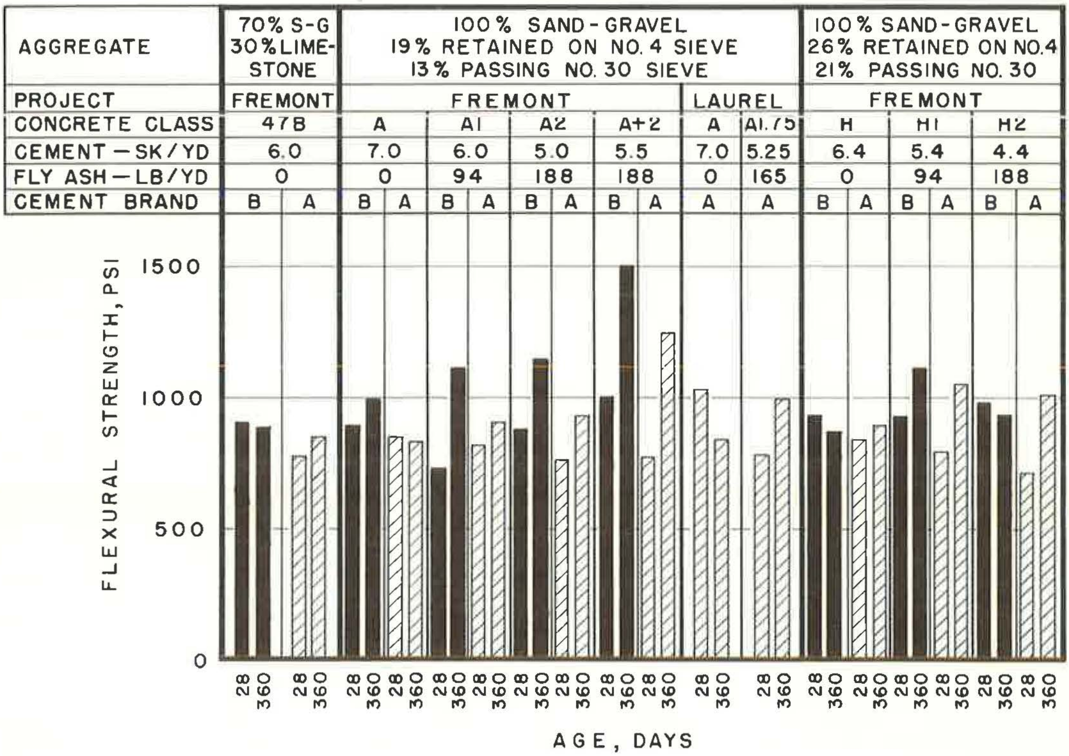

Figure 3. Flexural strength of concrete beams.

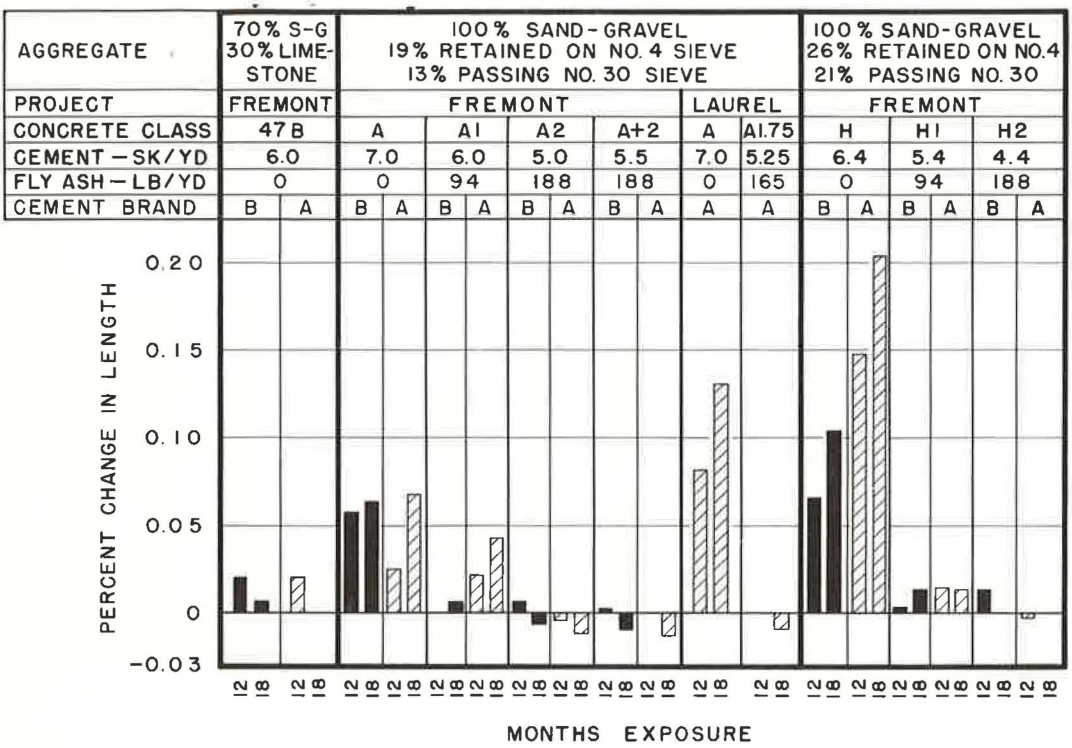

Figure 4. Length change of concrete beams in wetting and drying exposure.

representing similar concrete on the Laurel project expanded considerably more than 0.05 percent at 12 mo of exposure. This was an indication that damage could be expected in these sections because of expansion caused by cement-aggregate reaction.

In all but one instance the substitutions of 94 lb of fly ash was sufficient to inhibit the cement-aggregate reaction within a safe limit. The one exception was Class A1 concrete with brand A cement. Although the expansion of these beams was within safe limits at 12 mo, they were expanding at a rapid rate after 18 mo of treatment. Detrimental expansion was completely inhibited in all sections with a substitution greater than 94 lb of fly ash per cubic yard of concrete.

Freezing and Thawing Exposure

Beams representing each class of concrete were also allocated to a directional-freezing and uniform-thawing exposure (2). These beams were frozen by contact of the molded 4- by 16-in. face of the beams with freezer plates until the temperature at the center of the beams was reduced to -20 F. The beams were then thawed by circulating air maintained at a temperature of 70 F with steam. Four cycles of freezing and thawing were produced each day.

Periodically the test beams were measured for loss in sonic modulus of elasticity (E) and change in length. All sets of beams were removed from the test when their average loss in sonic E was 30 percent or more, or after 200 cycles of freezing and thawing, whichever occurred first.

Durability factors were computed by the method described in ASTM Designation: C260-54 and are shown in Figure 5. This is a severe freezing and thawing test, and previous tests indicate that a durability factor of 40 or more is indicative of durable concrete. Based on this premise, all concretes tested were durable. However, all classes of concrete made with fly ash had a durability factor of 100, indicating that concrete made with these materials was practically unaffected by 200 cycles of freez-

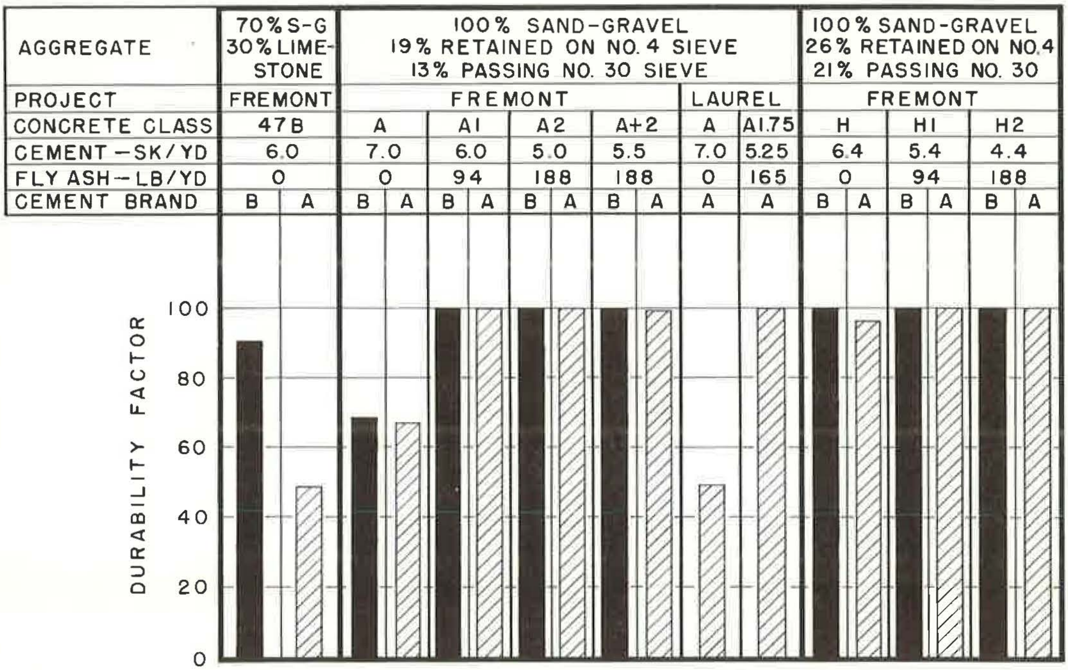

Figure 5. Durability of beams subjected to directional freezing and uniform thawing exposure.

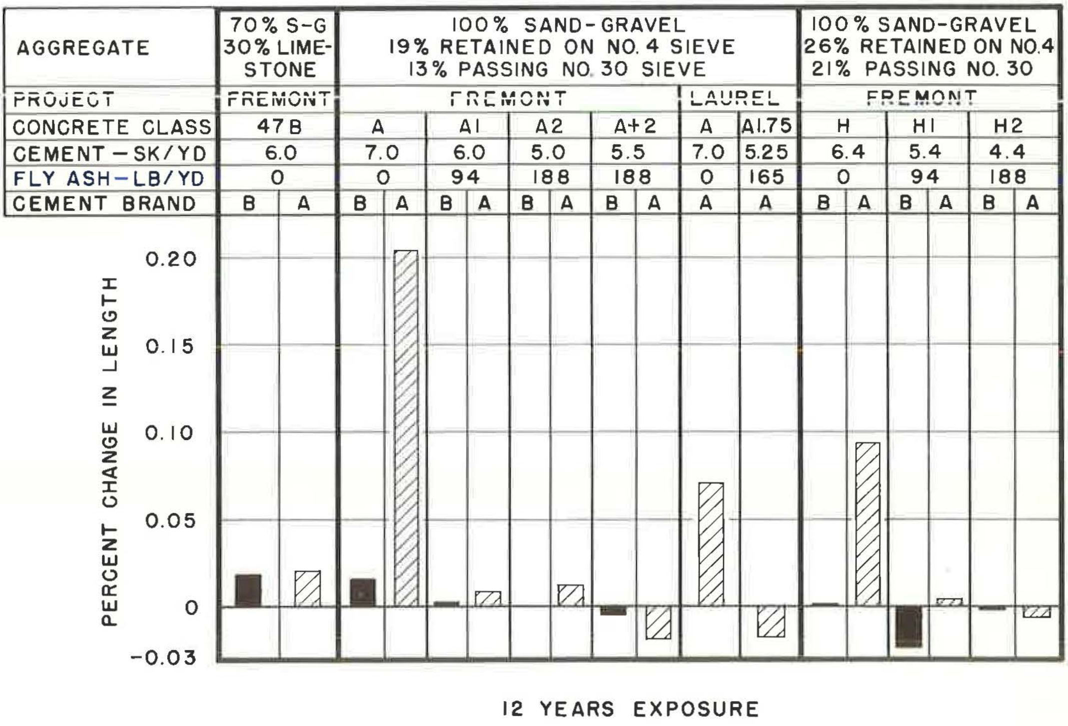

Figure 6. Length change of concrete beams in outdoor exposure yard.

ing and thawing. The inclusion of fly ash in the mixture increased the durability of the concrete when the air content was held at an adequate level.

Outdoor Exposure

Four 6- by 6- by 30-in. concrete beams representing each class of concrete were cast with measuring plugs set at 20-in. centers in their top and side faces. These beams were cured in the same manner as the small beams and then placed in an outdoor exposure yard. They were laid in parallel rows on a 4-in. sand cushion with sufficient space between them to provide maximum exposure to the sun.

The length changes of the beams after 12 yr of exposure are shown in Figure 6. These measurements indicate that the 100 percent sand-gravel concrete made with brand A cement has developed excessive expansion or is growing at a rate that will produce excessive expansion in a few years. None of the classes using fly ash or the concrete made with crushed limestone developed expansion that could be considered excessive. Also, the 100 percent sand-gravel aggregate concrete made with brand B cement did not grow excessively.

CHANGE IN LENGTH OF CONCRETE PAVEMENT

The changes in length of the pavement sections representing each class of concrete have been measured periodically since the project was constructed. For these measurements, stainless steel reference plugs were set in the plastic concrete at each special test area during construction of the pavement. The plugs were embedded in the concrete at 20-in. centers in a row that extended across the pavement perpendicular to the centerline and midway between contraction joints. Initial measurements were made at 30 days age and then periodically ever since with a 20-in. strain gage using an Invar steel bar as a standard.

Concrete pavement is constantly undergoing changes in volume because of variations in prevailing conditions. Temperature changes cause the concrete to fluctuate almost continuously day and night. Variations in moisture will also cause changes in volume which may or may not vary to a great extent each day but will certainly vary during the year. A cement-aggregate reaction will also cause a change in volume of concrete, but this change is always positive and permanent. Concrete will fluctuate in volume because of variations in temperature or moisture, but a continuous growth over a period of years is indicative of permanent damage which may be caused by a cement-aggregate reaction and/or freezing and thawing. Because no damage from freezing and thawing was apparent on either project, any permanent expansion probably resulted from a cement-aggregate reaction.

Because of fluctuations, exact values of expansions or contractions cannot be measured at any specified time, and only trends should be considered. Curves indicating these trends are plotted by the least squares method in Figure 7.

Detrimental expansion was inhibited in the concrete made with substitutions of crushed limestone and in all classes of concrete made with fly ash; in fact, most sections using fly ash had some shrinkage. Class A and Class H concrete using brand A cement without fly ash expanded considerably on the Fremont project. These sections started to map-crack about the fifth or sixth year and are in poor condition at the present time. Test sections on the Laurel project made with Class A concrete and brand A cement have not expanded an alarming amount for some unknown reason, but there are areas outside the location where the measuring plugs were set in which this class of concrete is severely map-cracked and there is considerable evidence of expansion.

Sections constructed on the Fremont project with Class A or H concrete (no fly ash) using brand B cement did not expand enough during 12 yr to cause any serious damage to the concrete. However, some areas constructed with Class H concrete are beginning to develop faint map-cracking.

AGGREGATE	70% S-G 30% LIME-STONE		100% SAND-GRAVEL 19% RETAINED ON NO. 4 SIEVE 13% PASSING NO. 30 SIEVE										100% SAND-GRAVEL 26% RETAINED ON NO.4 21% PASSING NO. 30					
PROJECT	FREMONT		FREMONT								LAUREL		FREMONT					
CONCRETE CLASS	47 B		A		A1		A2		A+2		A	A1.75	H		H1		H2	
CEMENT – SK/YD	6.0		7.0		6.0		5.0		5.5		7.0	5.25	6.4		5.4		4.4	
FLY ASH–LB/YD	0		0		94		188		188		0	165	0		94		188	
CEMENT BRAND	B	A	B	A	B	A	B	A	B	A	A	A	B	A	B	A	B	A

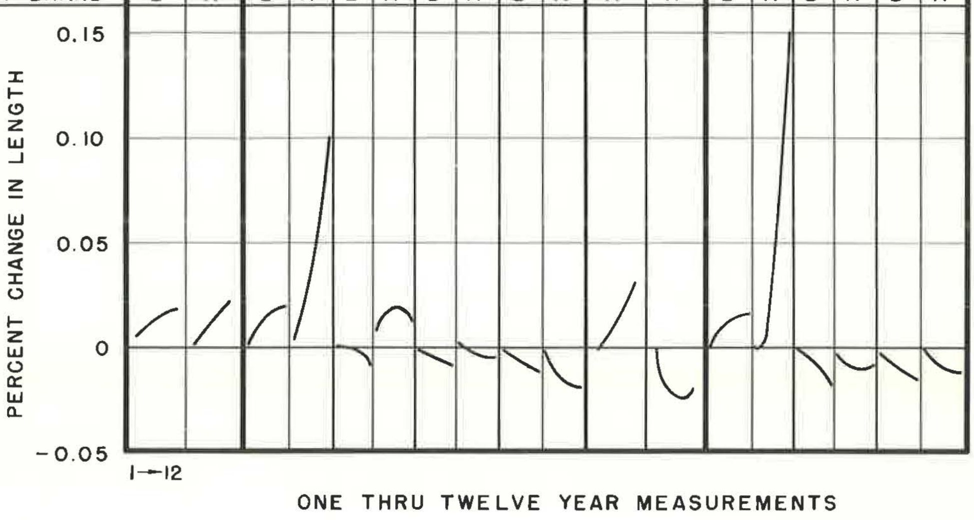

Figure 7. Linear change of concrete pavement.

PAVEMENT CONDITION

The pavement on both projects has been inspected at various intervals for the development of cracks and to determine the general condition of the concrete. At the time of the last survey (April 1962), map-cracking and evidence of expansion was observed on all sections constructed with sand-gravel aggregate concrete and portland cement A. Most areas in these sections were damaged to the extent that a protective covering or some other type of repair was needed. Similar sections constructed with cement B are in much better condition, and only a few localized ones show signs that map-cracking may be developing.

There was no evidence of map-cracking or expansion in the sections constructed with concrete containing 165 lb or more of fly ash. Some of the sections on the Fremont project made with concrete containing fly ash developed transverse cracks at an early age, but at the present time there are more transverse cracks per unit length in the sand-gravel aggregate concrete made without fly ash than there are in corresponding sections made with fly ash. Some of the 1,800-ft sections on the Fremont project constructed with fly ash are entirely free of cracks of any kind and appear to be in perfect condition.

Rebound hammer tests taken on the pavement at the time of the last survey indicated that the strength of the sand-gravel aggregate concrete containing fly ash was higher than the strength of similar concrete made without fly ash.

The condition of the concrete sections at the present time confirms most of the laboratory tests made previously. Some sections constructed with brand B cement did not develop as much growth as was anticipated, but all concrete made with brand A cement that expanded a considerable amount in the wetting and drying test also expanded considerably during service. In all cases, the use of fly ash in the concrete reduced expansion and increased compressive strength both in the laboratory tests and in the concrete pavement. The laboratory tests also indicated that all types of concrete were durable in freezing and thawing, and there was no evidence of damage from freezing and thawing on either project. The condition of the concrete sections at the present time is also proof that sound and durable concrete pavement can be constructed with Nebraska sand-gravel and portland cement if the proper amount of a good-quality fly ash is used in the mix.

SUMMARY

Observations and tests on the Laurel and Fremont test projects during construction and during a subsequent service period of 12 to 13 yr may be summarized as follows:

1. The addition of fly ash to a sand-gravel aggregate concrete presented no special problems in batching and placing the concrete, and the additions made the concrete more workable except during periods of excessively high temperature and low humidity.
2. Although concrete made with fly ash had slightly lower early strengths than corresponding concrete without fly ash, its strengths, both flexural and compressive, were higher at later ages.
3. The use of fly ash in sand-gravel aggregate concrete increased its durability in freezing and thawing when the air content was held at an adequate level.
4. Expansion and map-cracking because of cement-aggregate reaction was satisfactorily inhibited with the use of sufficient quantities (over 94 lb/cu yd) of fly ash in sand-gravel aggregate concrete.
5. Expansion because of cement-aggregate reaction was also inhibited by using 30 percent crushed limestone in the sand-gravel aggregate concrete.
6. All sections of concrete constructed with 165 lb or more of fly ash per cubic yard of concrete are in better condition than sections constructed with corresponding concrete without fly ash. Some of the sections constructed with concrete using fly ash are still free of cracks and apparently in perfect condition after 13 yr of service.

REFERENCES

1. Bollen, R. E., and Sutton, C. A. Pozzolans in Sand-Gravel Aggregate Concrete. Highway Research Board Proc., Vol. 32, pp. 317-328, 1953.
2. Bollen, R. E. Durability of Portland Cement Concrete Determined by Primary Directional Freezing and Uniform Thawing. Highway Research Board Proc., Vol. 28, pp. 218-232, 1948.

Use of Fly Ash as Admixture in an Experimental Pavement in Kansas

W. M. STINGLEY and R. L. PEYTON
Respectively, Concrete Engineer and Assistant State Highway Engineer,
State Highway Commission of Kansas

Although fly ash has been widely used as an admixture in mass concrete, its use in highway construction has been more limited. It has been used in Kansas as a replacement for a part of the cement in one experimental paving project which has been under traffic for 14 yr. Five brands of cement with dissimilar characteristics were used in combination with aggregate and fly ash, each from a single source. Although this project has been reported previously, no detailed study of the fly ash concrete sections has been published. Results varied widely with change in cement brand, but the reasons for the changed results are not clearly understood.

Evaluation of the effectiveness of the fly ash in decreasing map-cracking is based on the supposition that reductions in flexural strength accurately reflect increases in map-cracking as here defined.

•IN 1949 the Kansas Highway Commission, in cooperation with the U. S. Bureau of Public Roads and assisted by Kansas State University, constructed an experimental pavement with sections which included concrete containing fly ash. Twelve 488-ft sections were built in which fly ash was used to replace a portion of the cement. The project, near McPherson, has been reported previously (1, 2); this paper deals with the fly ash concrete sections in greater detail.

The test pavement is 22 ft wide, 9 in. thick, and mesh reinforced. Grooved contraction joints formed and finished manually are spaced at 20 ft 4 in. Only expansion joints and construction joints are doweled. The slab was placed on a dense-graded granular subbase, 4 in. thick. The subgrade soils are reasonably uniform throughout the project.

The aggregate chosen for this project was a fine-graded sand-gravel, hardly more than a coarse sand, furnished as a mixed or one-component material. The average fineness modulus was 3.58. It was produced from a deposit on the Republican River which heads in Colorado and flows into the Kaw River in central Kansas. Aggregate from this stream has long been considered to be responsible for severe map-cracking of concrete and its use is seldom permitted for other than below-ground structures such as culverts. Gibson (3) and Scholer and Gibson (5) showed that concrete containing this or similar aggregate could be made less subject to map-cracking by the addition of crushed limestone at the rate of 30 percent or more of the total weight of the aggregate, but a less expensive remedy was sought. The concrete was proportioned by absolute volumes with minimum cement content and maximum water controlled.

Fly ash was obtained from the Chicago area. It may not have complied in all respects with present ASTM requirements, and some tests now required were not made. Results of the tests that were made are as follows: reduction in alkali, 33.8 percent; compressive strength, 1,131 psi; fineness (Blaine), 4,000 sq cm; SiO_2, 45.65 percent; Al_2O_3, 19.89 percent; MgO, 0.94 percent; SO_3, 1.77 percent; and loss on ignition, 2.31 percent.

Five brands of cement with and without substitutions of fly ash or additions of crushed limestone were used in the project. The results changed sharply when one

---

Paper sponsored by Committee on Chemical Additions and Admixtures for Concrete.

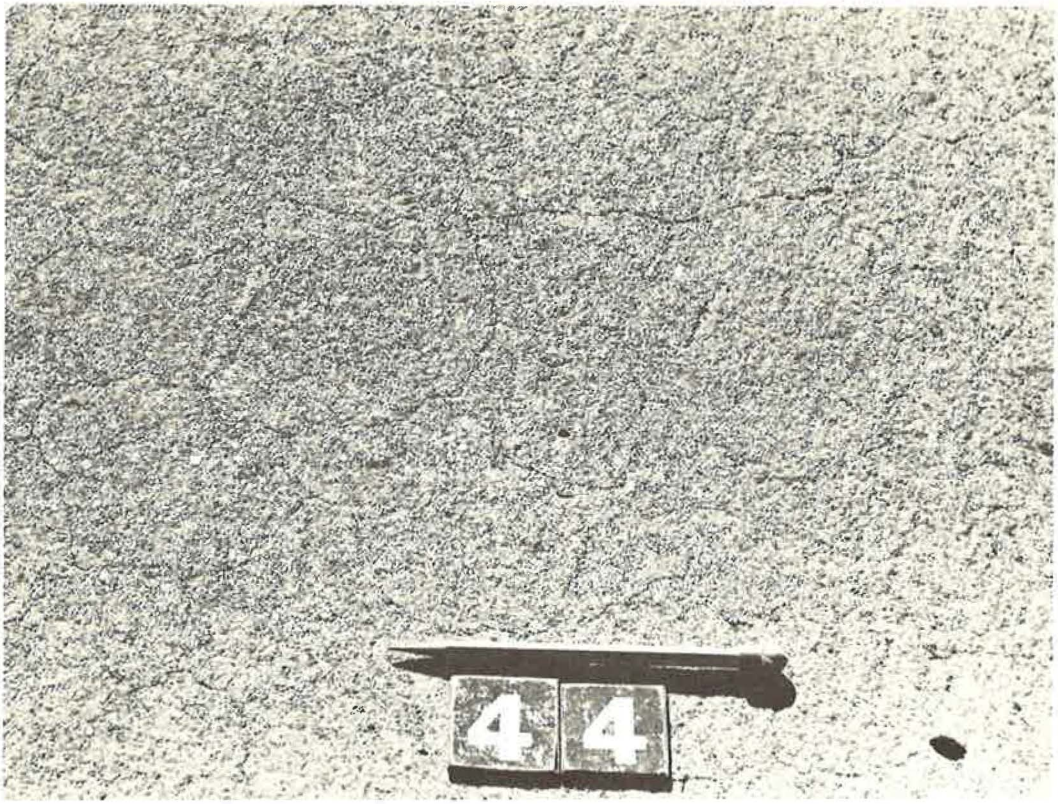

Figure 1. Shallow pattern cracking.

Figure 2. True map-cracking.

brand of cement was substituted for another. Concrete containing each cement was benefited by the fly ash to some extent, but the improvement varied from slight with one cement to marked with others. Test sections were constructed with and without air entrainment.

Flexural strength was obtained by testing 6- by 9- by 48-in. beams made at time of construction from concrete taken from the paving mixer. A 4- by 10-ft slab, 9 in. thick, was cast near the boundary of the right-of-way near each experimental section. These slabs had partial-depth wood dividers at 6-in. centers to separate the slab into test beams having, roughly, an I-beam cross-section. The slabs were cured in an identical manner with the pavement proper and were given no special attention thereafter, other than an occasional shouldering up. Tests were normally made each spring and fall, a total of 40 tests for each section, but a few beams were lost through breakage or were stolen.

Although other pozzolans were used in the test road, only the fly ash concrete sections are considered here, along with appropriate control sections in which only the basic aggregate was used or to which limestone aggregate was added. The comparisons will be based on the premise that increased map-cracking is reflected in decreased flexural strength. Some of the earlier work on sand-gravel concrete deterioration done in the area was reported by the Engineering Experiment Station of Kansas State College and by the Portland Cement Association (4).

A description of map-cracking is taken from that report:

> The deterioration which is occurring in some sand-gravel pavements and structures in Kansas, Nebraska, Iowa and Missouri is evidenced by abnormal expansion, map cracking, and loss of flexural strength.
>
> The first visible evidence of this deterioration is usually a series of connected cracks on the top surface of a pavement, visible to the naked eye after a light application of water as the surface begins to dry. The map cracking usually forms oblong boundaries with an area of eight to twenty square inches inside the cracks. The cracking starts on the exposed surface of a pavement or structure and deepens as the deterioration progresses.
>
> In the advanced stages, the cracks may progress until they reach the bottom side of the pavement. These cracks tend to form lines parallel to the centerline of the pavement. This type of cracking should not be confused with cracks developing on the surface of concrete pavement directly above the wire mesh where the reinforcing has been placed too near the surface. Neither should this cracking be confused with surface checking, shrinkage or cracking due to settlement and loads, nor with cracks caused by unsound coarse aggregate.

Varying amounts of shallow pattern cracking were observed in all test sections but did not appear to indicate declining utility of the pavement. Figure 1 shows this type of cracking. However, true map-cracking, shown in Figure 2, is usually a forerunner of slab disintegration. Measures to reduce or retard it, while necessary, are at some locations so costly as to preclude the use of concrete pavement.

The substitution of fly ash for approximately 25 percent of the weight of cement tended to produce concrete of adequate flexural strength with each cement for each age at which tests were made. Figure 3 is a plot of flexural strength and elapsed time after construction for one of the cements. Each point is an average of two tests made on one beam. It will be noted that there are strength variations from spring to fall and from year to year, and that these variations are large when fly ash is used. The minimum values were still, in most cases, higher than attained by test beams taken from the companion sections of concrete not containing fly ash.

Figures 4 through 8 are similar plots, but the values have been consolidated and smoothed to show trends more clearly. Figures 4, 5, and 6 are flexural strength-time plots for cements C, N, and H, respectively. These cements are of similar chemical composition and respond in a similar manner when a portion is replaced by an equal

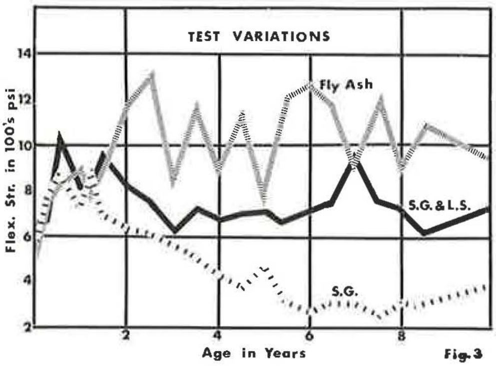

Figure 3.

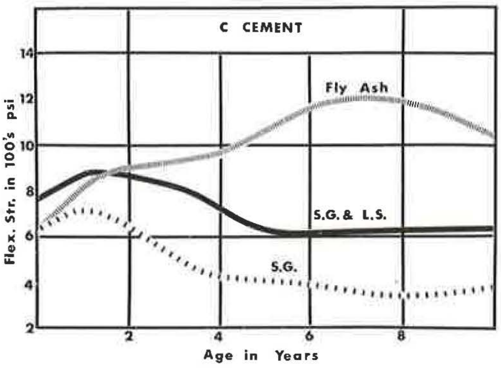

Figure 4.

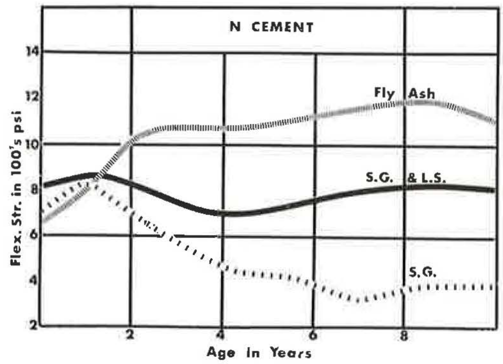

Figure 5.

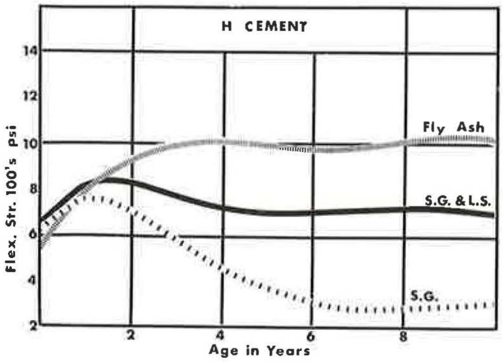

Figure 6.

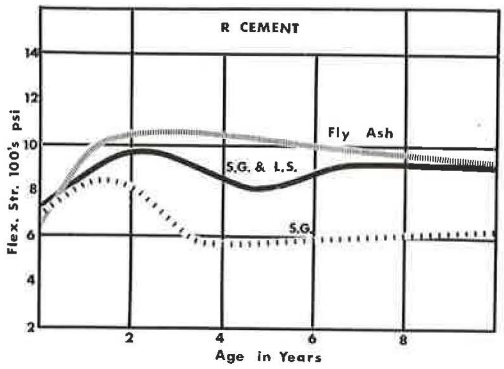

Figure 7.

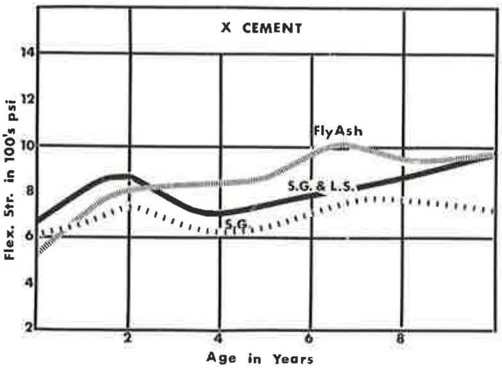

Figure 8.

TABLE 1

CEMENT COMPOSITION

Brand	SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	CaO (%)	MgO (%)	SO_3 (%)	Ign. Loss (%)	Na_2O (%)	K_2O (%)	Tot. Alk. (%)	C_3S (%)	C_2S (%)	C_3A (%)	Al: Fe
C	20.8	5.6	2.9	63.5	3.1	2.4	0.9	0.24	0.55	0.60	52.0	20.4	9.9	1.93
N	20.7	6.0	3.4	63.2	3.0	2.0	1.1	0.25	0.45	0.55	49.3	22.2	10.1	1.76
H	22.4	5.8	2.8	64.5	0.6	1.7	1.2	0.29	0.51	0.63	44.5	30.8	10.0	2.07
R	22.4	4.3	2.8	62.2	4.1	1.8	1.7	0.16	0.59	0.55	44.4	30.9	6.3	1.53
X	21.4	5.6	2.9	64.4	1.8	1.7	1.4	0.25	0.37	0.49	51.4	23.0	10.0	1.93

weight of fly ash. Without additions of fly ash or limestone, peak flexural strength is reached during the first year or shortly thereafter, and the strength of each declines at nearly the same rate for the remainder of the 10-yr period. When limestone is added, the peak strength may be somewhat higher and is attained later, and the decline occurs at a slower rate, leveling off at higher values. The concrete containing fly ash does not reach the level of flexural strength attained by the reference concrete during the first few months, but the flexural strength is adequate during this period. During the remainder of the test, the flexural strength of concrete containing fly ash is much higher than that of the reference concrete.

Figure 7 is a plot of flexural strength and time for concrete containing cement R, which is a Type II cement. Here fly ash appears to have been unnecessary. All three classes of concrete produce nearly the same flexural strength, and the pavement sections they represent appear to be of equally good quality. Even here, however, there is some advantage shown for the fly ash concrete sections over those with basic aggregate and those with limestone.

Figure 8 supplies the same information for the concrete containing cement X. Brand X is not a Type II cement but exhibits results similar to those obtained with brand R. The chemical composition of cement X is not unlike that of cements C, N, and H, but there appears to have been little need for the modifying influence of fly ash as far as flexural strength is concerned. The pavement proper, however, represented by these test beams, is showing signs of distress in the basic aggregate section, though at a slower rate and in a somewhat different manner. The crack pattern, although not a fully developed map-cracking, is more extensive and the cracks are deeper and more stained than the surface cracking found in the cement R section without fly ash or limestone. However, the pattern does not approach in severity the cracking observed in the sections containing cements C, N, and H in which no admixture was used. When cement X is combined with fly ash, a shallow surface cracking occurs similar to that found in the limestone aggregate sections.

Table 1 is a tabulation of cement composition. Average values are shown for all tests made on each cement during construction. Variations of individual tests from the averages were small.

No work was done with widely varying amounts of fly ash, the amount substituted being between 24 and 27 percent. It is possible that different proportions of fly ash and cement would perform in a different manner, and some additional economy may be possible.

Control of air entrainment in the fly ash sections was difficult. Much larger than normal amounts of air-entraining admixtures were required, and there are some differences in the manner in which flexural strength of the three classes of concrete under consideration vary with time. The margin of superiority in flexural strength of the air-entrained fly ash concrete sections over the air-entrained limestone and basic aggregate sections is less than with the non-air-entrained classes, but still exists. Although air entrainment tended to smooth the flexural strength curves of the basic aggregate and limestone aggregate concrete sections, it did not when combined with fly ash concrete. This may be due to smaller moisture changes in the air-entrained concrete, but why this does not also apply to the air-entrained fly ash concrete is uncertain. It may be that moisture change is reduced to the same degree, but that fly ash concrete is simply more sensitive to a given amount of change. It may also be true that the amount of air entraining may vary to a greater extent in the fly ash concrete because, as mentioned, control was difficult.

Although air entrainment seemed to increase transverse and longitudinal cracking in most of the other test sections, such an effect was not observed in the sections in which fly ash was used.

CONCLUSIONS

1. The substitution of fly ash for 25 percent of the weight of cement reduced surface cracking and eliminated map-cracking as defined.
2. Flexural strength at early ages of concrete containing fly ash was less than for the reference concrete but was adequate and much higher at all later ages to 10 yr.
3. Cement brand appeared to be an important factor in the degree to which fly ash was beneficial, but some improvement was noted with all the brands used in the test.
4. Air entrainment tended to reduce but not eliminate the advantage shown for flexural strength of the fly ash sections over the reference concrete sections.
5. Many large areas in the central plains, considered poor in concrete aggregate, have abundant supplies of coarse sands comparable to the aggregate used in this project. As mentioned earlier, although referred to as a sand-gravel, it contains little gravel as ordinarily defined. Whereas concrete composed of such aggregate barely qualifies as concrete by definition and is often subject to map-cracking, it has been demonstrated that it is capable of good performance in a pavement slab with a reasonable amount of cement and fly ash.

REFERENCES

1. Peyton, R. L., Stingley, W. M., and Myer, Richard C. Effect of Pozzolans Added to Sand-Gravel Concrete Pavement. Highway Research Board Proc., Vol. 34, pp. 301-319, 1955.
2. Stingley, W. M., McNeal, John D., and Peyton, R. L. The McPherson Test Road: Tenth Year Report. Highway Research Board Proc., Vol. 39, pp. 191-204, 1960.
3. Gibson, W. E. Effect of Various Aggregates upon the Cement-Aggregate Reaction. ACI Journal, pp. 44-51, June 1948.
4. A Study of Special Concrete Problems in Kansas, Nebraska, Iowa and Western Missouri. Engineering Experiment Station, Kansas State College and Portland Cement Assoc., May 1946.
5. Scholer, C. H., and Gibson, W. E. Effect of Various Coarse Aggregates upon the Cement-Aggregate Reaction. Proc. Amer. Conc. Inst., Vol. 44, pp. 1009-1032, June 1948.

Use of Fly Ash in Concrete by the Alabama Highway Department

J. A. HESTER and O. F. SMITH
Respectively, Assistant Testing Engineer and Chief Chemist, Alabama State Highway Department

Several concrete bridges and pavements containing fly ash as an admixture to the concrete were constructed in Alabama between 1955 and 1963. Results of experimental tests on the fly ash and concrete containing fly ash are included in this description to illustrate some of the reactions expected to happen in these concrete structures. The mixture proportions, mixing and placement characteristics, and test results of the concrete are given to explain some of the problems and advantages resulting from the use of fly ash as an admixture in concrete.

•THE FIRST use of fly ash in concrete by the Alabama State Highway Department resulted from a 2-yr investigation involving extensive chemical and physical experiments with several types of pozzolanic materials conducted in the Chemical and Physical Sections of the Highway Department laboratory (1, 2). With the reports of these experiments is included a description of the Dauphin Island bridge (2), the largest of three concrete bridges containing fly ash that make up a large portion of the Overseas Highway, extending from Cedar Point, Ala., across the Mississippi Sound to Dauphin Island. The Dauphin Island bridge was constructed during 1954 and 1955. Since then, numerous concrete pavements and bridges containing fly ash have been constructed in Alabama.

BRIDGES

Although details of construction and experimental data concerning the Dauphin Island bridge (Fig. 1) have been published, some of the conclusions gathered from this work must be reviewed to explain certain sections of the following text.

The concrete deck section contains 5.76 sk of Type II cement per cubic yard, 23.5 lb of fly ash per sack of cement, 3 percent entrained air, quartz sand, and gravel composed of a mixture of chalcedonic chert and a quartzite. The steel pile incasements and caps contain 4.96 sk of Type II cement per cubic yard and 23.5 lb of fly ash per sack of cement, 3 percent air and the same type of fine and coarse aggregate contained in the deck section.

The fresh concrete had excellent workability that made it possible to use less water, resulting in lower slump, higher strength, and less shrinkage. A large part of the coarse aggregate was composed of chalcedonic chert, a fraction of which was definitely considered to be alkali reactive.

Compressive strengths of 1-yr cylinders from the deck section concrete averaged 9,800 psi, and the 7-yr test averaged 10,000 psi. It is doubtful if future tests will produce significant gain as the sand and coarse aggregate particles were shattered in both the 1- and 7-yr tests. Further tests revealed that the absorption was insignificant and there were no signs of alkali-reaction rims around any of the aggregate particles.

The occasional use of fly ash in concrete continued until May 1960, when "Special Provisions" were issued by the Alabama State Highway Department requiring the use

---

Paper sponsored by Committee on Chemical Additions and Admixtures for Concrete.

Figure 1. Dauphin Island bridge.

of fly ash and entrained air in all highway department concrete bridges. In addition, special provisions were, and still are, included in concrete pavement contracts specifying the amount of fly ash, cement, and entrained air for each project. These quantities are based on actual concrete mixtures proportioned, mixed, and tested in the laboratory for each project.

The prospective amount of fly ash, required as a result of the Highway Department Special Provision, was so large that it was doubtful if it could be furnished by the existing local producers. In addition, the fly ash from the original source had decreased in quality to such an extent that it could not be depended on to consistently meet highway department specifications. According to Section 806.01 of the specifications, fly ash shall consist of the finely divided residue that remains after burning coal at high temperatures and shall meet the following requirements:

pH (1 part fly ash 1 part water by wt)	7.0, min;
SiO_2 (%)	40.0, min;
Al_2O_3 (%)	15.0, min;
MgO (%)	5.0, max;
Available alkali as Na_2O (%)	1.5, max;
Shrinkage (%)	0.09, max;
Loss on ignition (%)	6.0, max; and
Passing No. 325 screen (%)	75.0, min.

It was also difficult to obtain fly ash in bags as required for many of the smaller concrete jobs.

In the meantime the Alabama and Georgia power companies were jointly completing construction of a large steam electric generation plant on the banks of the Coosa River near Wilsonville, Ala. This plant was completed and put into operation only a short while before the highway department's special provisions went into effect. It contains very efficient coal grinding and burning equipment and the latest type of electrostatic precipitation units.

Fly ash from this plant is a light gray product resembling the usual color of Type I portland cement. The chemical analysis (Table 1) shows the percent loss, carbon, and iron to be relatively low, whereas the percent silica and alumina are comparatively

TABLE 1

CHEMICAL ANALYSIS OF WILSONVILLE FLY ASH

Analysis	Value
Sp. gr. (77/77 F)	2.133
Loss on ignition (%)	2.35
pH	11.95
Surface area, Blaine	3557
SiO_2 (%)	50.95
Al_2O_3 (%)	29.17
Fe_2O_3 (%)	5.16
MgO (%)	1.10
CaO (%)	1.07
SO_3 (%)	0.26
Available sodium as Na_2O (%)	0.28
Available potassium as K_2O (%)	1.08

TABLE 2

ANALYSIS OF SEPARATE SCREEN SIZES OF WILSONVILLE FLY ASH

Item	Fraction Retained on 200	Fraction Pass 200, Ret. 325	Fraction Pass 325
Screen Fraction:			
Retained on 200 (%)	86.90	0	0
Pass 200, ret. 325 (%)	8.90	49.70	0
Pass 325 (%)	4.20	50.30	100
Analysis:			
Surface area, Blaine	1,563	2,674	4,113
Sp. gr. (77/77 F)	1.765	1.995	2.237
Loss at 110 C (%)	0.15	0.17	0.10
Loss at 1,100 C (%)	3.53	2.19	2.00
C (%)	3.00	1.90	1.68
SiO_2 (%)	53.60	52.15	51.60
Al_2O_3 (%)	28.54	30.08	30.65
Fe_2O_3 (%)	4.96	5.44	5.68
CaO (%)	2.09	2.35	2.55
MgO (%)	1.33	1.22	1.30
P_2O_5 (%)	0.45	0.57	0.66
TiO_2 (%)	1.30	1.38	1.50
MnO_2 (%)	0.001	0.001	0.001
Water soluble SO_3 (%)	0.14	0.16	0.26

TABLE 3

INGREDIENT PROPORTIONS AND PROPERTIES OF MORTAR CUBES, OTTAWA GRADED SAND

Fraction	Cube No.	Cement (lb)	Sand (lb)	Fly Ash (lb)	Water	Flow (%)	Shrinkage	Compressive Strength (psi)							
								7 Day	% Control	28 Day	% Control	60 Day	% Control	90 Day	% Control
Control	1	5	13.65	0	950	92	0.049	5,389	—	6,156	--	7,759	--	8,020	--
Ret. 200	2	5	10.90	1.80	1,132	105	0.050	5,402	100.2	7,445	120.9	8,591	110.4	8,661	108.0
Pass 200, ret. 325	3	5	10.90	2.05	1,155	115	0.094	6,022	111.7	8,793	142.8	10,475	135.0	10,795	134.6
Pass 325	4	5	10.90	2.30	1,037	108	0.094	6,937	128.7	10,237	166.3	12,638	162.9	12,417	154.8

TABLE 4

AVAILABLE ALKALI AND SILICA (Wilsonville Fly Ash)

Age (days)	Na_2O (%)	K_2O (%)	SiO_2 (%)		
			HCl Sol.	NaOH Sol.	Total Sol.
(a) Sample A					
7	0.05	0.32	4.40	1.97	6.37
14	0.08	0.61	5.87	5.24	11.11
21	0.12	0.98	11.45	4.42	15.87
28	0.12	1.12	13.39	1.89	15.88
60	0.26	1.78	18.91	5.10	24.01
(b) Sample B					
7	0.03	0.51	5.08	1.63	6.71
14	0.08	1.02	8.25	5.43	13.68
21	0.08	1.66	11.47	1.30	12.79
28	0.11	1.92	12.24	1.00	13.24
60	0.14	2.24	19.30	5.01	24.31

high. Results from a very extensive examination of this fly ash and mortar containing it are shown in Tables 2, 3, and 4. Although the tests contained in this report represent only a few of those contained in the total investigation, the reactions should be closely related to those that occur in concrete structures.

Table 2 shows the gradation and chemical analysis on each of three separate screen fractions of Wilsonville fly ash. The samples represent the fly ash retained on the No. 200, passing the No. 200 and retained on the No. 325, and passing the No. 325 sieves. The larger amount of carbon is retained on the No. 200 sieve.

Table 3 contains the proportions of cement, fly ash, and graded Ottawa sand, percent flow, and shrinkage of the mortar in cubes representing fly ash from each of the sieve sizes, as well as in control cubes without fly ash. Results are also given of compression tests of the cubes at ages of 7 through 90 days. When fly ash from each sieve size was substituted for 30 percent of the sand, by volume, the cubes broke at higher strengths than the corresponding control cubes in every case. The finer the fly ash, the faster the reaction proceeded.

Table 4 gives the available alkali results (ASTM: C 311-61T) obtained on two samples of Wilsonville fly ash. Many additional tests were conducted by this method and tests were made for the acid-soluble and alkali-soluble silica at the indicated ages. Even with the high alkali content of the solution at 28 and 60 days, the formation of calcium silicate continued at a normal rate. This test is an indication of the rate of reaction of the fly ash at corresponding ages when contained in concrete subject to an average temperature of 100 F.

CONCRETE PAVING

At present, the Alabama State Highway Department has completed construction of 85 mi of Interstate four-lane concrete pavement. Of this number, 70 mi contain concrete with fly ash as an admixture and 15 mi contain concrete without fly ash. All pavement contains natural quartz sand fine aggregate and crushed limestone coarse aggregate, except for an 8.7-mi section containing "Roquemore" gravel

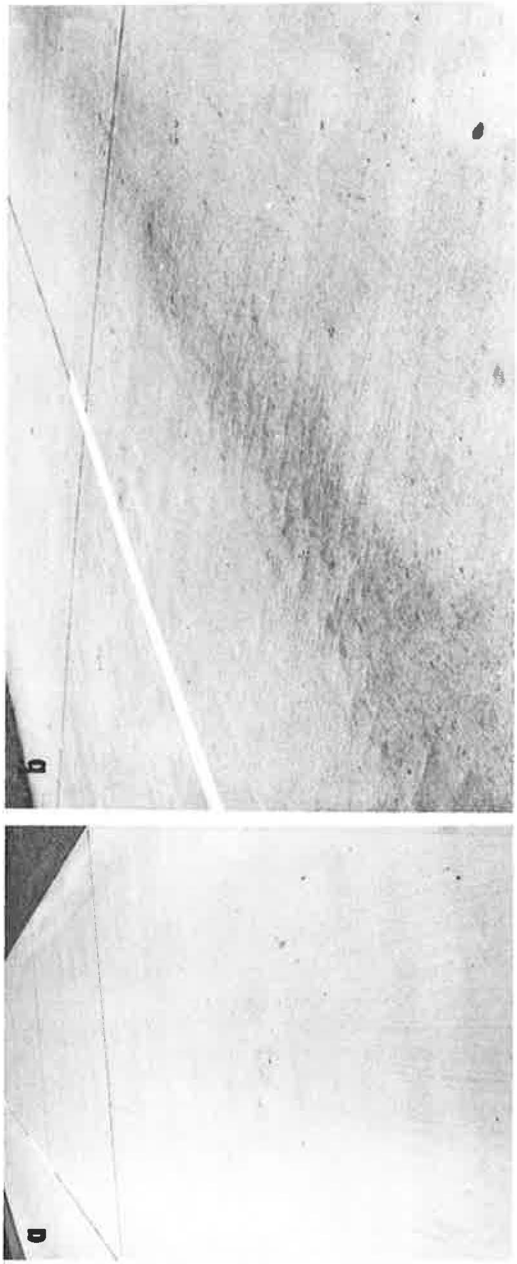

Figure 2. Concrete pavement: (a) with fly ash, and (b) without fly ash.

as coarse aggregate. The entire 85 mi of pavement is distributed over several Interstate projects.

Although the concrete is proportioned, mixed, and tested separately for each project, only four distinctly different mixtures are included. Three mixtures contain No. 4 to $1\frac{1}{2}$-in. crushed limestone as coarse aggregate and are related to such an extent that a direct comparison of the physical characteristics is possible. The fourth mixture contains No. 4 to $1\frac{1}{2}$-in. Roquemore gravel as coarse aggregate and is included because of a slightly higher cement factor and the potential reactivity of the gravel. Only one project is included under each mixture.

One of the first Interstate pavements is a 6.7-mi four-lane section, Project I-65-3(20), north of Birmingham (Fig. 2). It contains concrete without fly ash consisting of limestone, quartz sand, 4 percent entrained air, and 6 sacks of Type II cement per cubic yard of concrete. It is included because it was the first Interstate concrete mixture, and because it adjoins a 6.2-mi section of pavement, Project I-65-3(21), that contains the same components except for fly ash that replaces 8 percent of the sand by weight (Table 5).

Although the concrete without fly ash was proportioned for maximum workability, it was much more difficult to finish than the concrete containing fly ash. One reason for adding fly ash to the concrete mixture on Project I-65-3(21) was the repeated request for the addition by the concrete finishers who had previously been employed on a secondary concrete paving project using fly ash in the mixture. In addition to the increase in workability afforded by the fly ash, the concrete also excelled in the 7- and 28-day flexural and compressive strengths (Table 6).

The increased strength and workability of the fly ash concrete in relation to the concrete without fly ash led to the decision to cut the sand content and replace a fraction of the remaining sand with fly ash in future mixtures. Through numerous experimental mixtures, it was found possible to remove one sack of cement per cubic yard of concrete and enough sand to keep practically the same sand-cement ratio as contained in the concrete without fly ash and still maintain a workable mixture.

The concrete mixture containing the reduced cement factor was selected as the third mixture and is best illustrated by the concrete contained in Interstate Project No. I-20-1(14) (Fig. 3). This project is a 7.3-mi section of four-lane pavement located east of Birmingham, Ala., between Eden and Riverside. The concrete contains 5.04 sacks of Type II cement per cubic yard, and is of special interest because it is the lowest cement factor being employed in paving concrete by the State Highway Department. Proportions of the mixture were as follows: cement, 94 lb or 0.478 cu ft; water, 6 gal or 0.800 cu ft; fly ash, 17.9 lb or 0.141 cu ft; entrained air, 3 percent or 0.161 cu ft; sand, 188 lb or 1.140 cu ft; and stone, 465 lb or 2.637 cu ft. Coarse aggregate used was No. 4 to $1\frac{1}{2}$-in. dolomitic limestone (sp. gr., 2.83); fine aggregate was natural quartz sand (F. M. 2.30, sp. gr. 2.64). Cement factor was 1.26 bbl (5.04 sk) Type II cement per cubic yard of concrete.

As in the other fly ash concrete mixtures, this concrete was very easy to place and finish. As it happened, the job got off to a bad start. A small preliminary mix-up in aggregate and miscalculation of joint sawing schedule resulted in several uncontrolled cracks in the first mile of pavement. This was brought under control and the remainder of the job proceeded without incident. The pavement has one of the smoothest riding surfaces of all the pavements in the state.

TABLE 5

CONCRETE PROPORTIONS[a]

Project	Cement		Water		Entrained Air		Sand		Limestone		Fly Ash		Yield (cu ft)
	Lb	Cu Ft	Gal	Cu Ft	Percent	Cu Ft	Lb	Cu Ft	Lb	Cu Ft	Lb	Cu Ft	
I-65-3 (20)	94	0.478	5.75	0.766	4	0.180	182	1.103	330	1.973	-	-	4.500
I-65-3 (21)	94	0.478	5.75	0.766	4	0.180	164	0.993	330	1.973	15	0.110	4.500

[a] Coarse aggregate—No. 4 to $1\frac{1}{2}$-in. crushed limestone, sp. gr. 2.68; fine aggregate-natural quartz sand F. M. 2.55, sp. gr. 2.65; cement factor-1.50 bbl (bsk) Type II cement per cubic yard.

TABLE 6

STRENGTH OF CONCRETE

Concrete	Flexural Strength (psi)			Compressive Strength (psi)		
	No. Tests	7 Day	28 Day	No. Tests	7 Day	28 Day
Without fly ash	148	500	700	200	2,960	4,290
With fly ash	159	550	740	200	3,310	4,790

The physical tests on concrete cylinders, cores, and beams were of particular interest, which did not develop from the reduction in cement alone. The reduction of sand in respect to the stone as a result of the workability afforded by the fly ash was of equal interest. This resulted in a very noticeable increase in flexural strength when compared to the concrete with the higher cement factors (Table 7).

From the compressive strength results it is evident that although sufficiently high, they are somewhat lower at 7 and 28 days than those of the higher cement content concrete. The compressive strengths of the cores show very good strength gain and should compare very favorably with those of the higher cement factors. Results from cores of the concrete with higher cement factors were not available for corresponding test ages.

The flexural strengths exceeded those of any concrete paving tested in the laboratory, regardless of cement factor, at corresponding ages. The highest strength from any one test exceeded 1,300 psi at 28 days.

The fourth type of mixture is included primarily because the coarse aggregate is Roquemore gravel, which, as previously described, is a mixture of chalcedonic chert

Figure 3. Section of concrete paving containing fly ash.

TABLE 7

CEMENT FACTOR VS STRENGTH OF CONCRETE

Type	Cement	Flexural Strength (psi)			Compressive Strength (psi)				
		Avg. No. Tests	7 Day	28 Day	Avg. No. Tests	7 Day	28 Day	60 Day[a]	120 Day[a]
With Fly Ash	5.04	212	690	1,040	116	2,540	3,840	4,650	6,410
With Fly Ash	6.00	159	550	740	200	3,310	4,790	-	-
Without Fly Ash	6.00	148	500	700	200	2,960	4,290	-	-

[a] 60 and 120 day test on 4-in. diameter cores, avg. of 64 tests.

Figure 4. Pier and cap of Old Chicasaboque bridge near Mobile, Ala.

with variable proportions of quartzite. It is best illustrated by the 8.7-mi section of four-lane concrete pavement, Project I-65-1(25), located between Montgomery and Mobile, Ala. This gravel contains various amounts of loosely bonded quartzite that, when included in concrete, causes a very noticeable reduction in flexural strength. This, in addition to the round slick surface of other gravel particles, made it necessary to increase the cement factor slightly above that contained in the limestone mix. Proportions of the mixture were as follows: cement, 94 lb or 0.478 cu ft; fly ash, 16 lb or 0.118 cu ft; water, 5.5 gal or 0.733 cu ft; entrained air, 2 percent or 0.102 cu ft; sand, 175 lb or 1.059 cu ft; and gravel, 420 lb or 2.585 cu ft. Coarse aggregates used was No. 4 to $1\frac{1}{2}$-in. Roquemore gravel (sp. gr., 2.61); fine aggregate was natural quartz sand (F. M. 2.55, sp. gr. 2.65). Cement factor was 1.33 bbl (5.32 sk) per cubic yard of concrete.

Even the higher cement factor failed to bring the flexural strengths in range of that produced by the limestone concrete. The compressive strengths are, however, higher for the 7- and 28-day tests of the gravel concrete. The strength obtained by the laboratory for the 7-day flexural test was 750 psi. This exceeds the 7- and 28-day averages on the field tests of 520 and 620 psi, respectively. The 7-day compressive strength for the laboratory mixture was 3,530 psi, whereas the average compressive strengths for 7 and 28 days were 3,420 and 4,670 psi, respectively.

The history of concrete structures containing Roquemore gravel shows that many of the bridges containing high-alkali cement, and a few believed to contain low-alkali cement, are affected by alkali reaction (Fig. 4). In addition, several concrete structures containing this aggregate have shown very little effect of alkali reaction when containing either high- or low-alkali cement. In most of the deleteriously affected structures, surfaces of equal exposure in the same structure containing the same cement throughout vary from badly damaged to no damage at all. This is undoubtedly due to the variation of the amount of reactive material in the gravel. This has been confirmed through petrographic examinations, mortar bar and chemical tests. Low-alkali cement appears to be effective in reducing this reaction in most instances.

As an additional safeguard to concrete pavement containing this aggregate, low-alkali cement (less than 0.6 as Na_2O) and fly ash are both used. As related before, this is also true in the concrete of the Dauphin Island bridge and many more concrete bridges in Alabama containing reactive aggregate. Only time will tell if the 16 lb of fly ash per sack of low-alkali cement (25 percent by volume) is sufficient to prevent reaction in this pavement. The best assurance at present is that of all the State Highway concrete structures containing fly ash, none are showing effect of alkali reaction.

LABORATORY TESTS

So far, the tests on laboratory concrete have purposely been omitted. The large number of test results on field concrete samples are included to represent, as nearly as possible, the actual physical performance of the pavement. The only physical test included on laboratory concrete and not on field concrete is shrinkage. This test is conducted on 4- by 4- by 16-in. bars with gage plugs cast in each end. Measurements are made with a dial comparator graduated to 0.0001 in.

Bars containing concrete without fly ash are used as standards and are compared to bars with the same components with the exception of fly ash. These bars are removed from the molds after 24 hr and measured. They are then placed in moist storage for 7 days, measured, and placed in the open at atmospheric conditions for 21 days. They are next measured and returned to moist storage for 14 days, measured, and exposed to atmospheric conditions for the remainder of the test. After conducting this test on several concrete mixtures, it was found after 1 yr of exposure that no appreciable difference was found between the results from the concrete bars without fly ash and those with fly ash.

ECONOMY

In figuring the economy of fly ash as an admixture for concrete, it is first necessary to determine just what is meant by economy. If it is only the initial cost of fly ash in relation to the cement it replaces, then it will be necessary to discount such advantages as (a) aid in combating alkali-aggregate reaction expansion, (b) extra workability, (c) superior compressive and flexural strengths, and (d) decreased absorption. Although these advantages are hard to express in dollars and cents, they are certainly an important part of the economy. The initial cost of transportation and handling fly ash is, of course, variable; however, it is possible to arrive at a fair estimate from the prices that exist in Alabama.

In general, the Alabama Highway Department specifications allow for the reduction of one sack of cement per cubic yard of concrete and its replacement by an equal weight of fly ash. With the usual brands of fly ash found in this area, this amounts to approximately 25 percent by volume. The average price of bulk fly ash is $4.50 per ton. It is hauled in tank trailers, various types of covered trailers, and closed gondola railway cars. Bulk fly ash is stored in bins at concrete paving plants and many of the larger batching plants. Sacked fly ash is available in preweighed quantities according to the contractor's requirements at $7.00 per ton. It is usually shipped in box cars and suitable trailer trucks.

Transportation and handling charges vary, but from average data gathered from several projects most distant from the plant, the price is approximately $5.00 per ton. This makes the cost of bulk fly ash at these points $9.50 per ton and sacked fly ash $12.00 per ton. This amounts to an average of approximately one-half the price of portland cement.

CONCLUSIONS

From the data on structures discussed in this report and on the many more too numerous to include, the following conclusions are drawn:

1. Some of the advantages gained by the addition of fly ash to concrete are extra protection against alkali-aggregate reactivity, increase in workability, decreased absorption, and increase in compressive and flexural strength.
2. By taking advantage of the extra workability added to the concrete by fly ash, the amount of sand can be reduced, resulting in a decrease in the required amount of mixing water, a higher cement-to-sand ratio in the mortar, less shrinkage, and higher 7- and 28-day compressive and flexural strengths, as well as ultimate strengths.
3. Paving concrete containing fly ash is easily placed and finished. Under similar conditions it can be placed with less slump than concrete without fly ash without seriously affecting workability. This results in less shrinkage; however, shrinkage is not reduced to the extent that cracks are eliminated when improper paving methods are employed. Delayed sawing of contraction joints, improperly placed dowel bars, and many other factors affect fly ash concrete the same as concrete pavement without fly ash.
4. Throughout the many tests on concrete paving mixtures, no definite relation was found between flexural and compressive strengths. In most instances, sufficiently high compressive strength could be obtained with lower cement factors than were required for flexural strengths. Because flexural strength is also very dependent on the type

and gradation of coarse aggregate employed, sufficient cement was added to each mixture to attain the designed flexural strength with the type of aggregate employed.

5. Without regard to the benefits derived from the addition of fly ash to concrete, when based on the cost of the concrete without fly ash, the average cost of the fly ash mixture is less.

REFERENCES

1. Hester, J. A., and Smith, O. F. Alkali-Aggregate Phase of Chemical Reactivity in Concrete, Part I. Highway Research Board Proc., Vol. 32, pp. 306-316, 1953.
2. Hester, J. A., and Smith, O. F. Alkali-Aggregate Phase of Chemical Reactivity in Concrete, Part II. ASTM Spec. Tech. Publ. 205, p. 74, 1956.

Experimental Concrete Pavement Containing Fly Ash Admixtures

RONALD D. HUGHES
Research Engineer, Kentucky Department of Highways

A 2.388-mi section of four-lane highway in Louisville, Ky., was selected for an experimental fly ash concrete pavement installation. The project was divided into three sections: a control section and two experimental sections containing 94 and 140 lb of fly ash per cubic yard, respectively. The solid-volume of fly ash in excess of that required to replace one sack of cement was considered as fine aggregate. The water was adjusted to provide a slump of approximately 2½ in., and an air-entraining admixture was proportioned at the mixer to provide an air content of approximately 4.5 percent.

Beams and cylinders were cast from various random mixtures within each section. Flexural and compressive strength tests were made at 3, 7 and 28 days, and 3, 6 and 12 mo. Beams were also cast for freeze and thaw testing. Test results to date are included in the report, as well as a description of construction procedures and mix design methods.

Early strengths for concrete placed in the experimental sections were lower than those for concrete placed in the control section. On the basis of limited 3-mo age compressive strength tests, a gain in strength at later ages was achieved through the use of fly ash. No reduction in water requirement was gained through the addition of fly ash.

•IN 1962, the Kentucky Department of Highways began an investigation of the use of fly ash in portland cement concrete for pavements. An experimental project was established to gain experience in the addition of fly ash to concrete. The project was also to serve as a basis for evaluating the performance of a cement-fly ash concrete pavement as compared to that of a normal cement concrete pavement.

Approximately 2⅓ mi of urban, four-lane, divided highway on Poplar Level Road in Louisville, Ky., was chosen for this investigation. The project was divided into three sections: Control Section, Experimental Section A and Experimental Section B. A portion of pavement was placed in one of the experimental sections early in December 1962, and paving was then discontinued due to adverse weather. The major portion of pavement was placed during the period of May and August 1963. This report contains a brief description of the project and a summary of test results to date.

DESCRIPTION OF PROJECT

Two parallel 26-ft wide dual-lane pavements, 9 in. in thickness, were placed on a 4-in. insulation course of dense-graded limestone aggregate. The major portion of concrete used in each of the three sections was placed and finished by conventional mechanical methods. Concrete was placed in two lifts to facilitate the installation of wire mesh at a plane below the final surface one-third the pavement depth. Deformed dowel bars were installed at 30-in. intervals along the centerline of each dual-lane pavement and smooth dowel assembly devices were installed at 50-ft intervals at transverse joints. All joints were sawed.

Paper sponsored by Committee on Chemical Additions and Admixtures for Concrete.

Each material that was common in all sections was invariable in nature and source. Type I normal portland cement from one producer was utilized in all mixtures. The fine aggregate was natural sand and the coarse aggregate was crushed limestone ranging from 2.5 to 0.25 in. in nominal size. The fly ash was locally supplied and specified to meet the requirements of ASTM Designation: C 350-60T. The same brand and type of air-entraining admixture was added to all mixtures at the mixer. Both the cement and fly ash were supplied in bulk.

A slump of approximately 2½ in. and an air content of 4.5 ± 1.5 percent were maintained throughout. Concrete placed in the Control Section contained 6 sk of cement per cubic yard; a ratio of fine aggregate to total aggregate of 37 percent by weight was maintained. Concrete placed in Experimental Section A was proportioned to contain 5 sk of cement and 94 lb of fly ash per cubic yard. All mixtures for Experimental Section A were proportioned on a solid volume basis and the fly ash in excess of that required to replace one sack of cement was considered as fine aggregate. Thus, by deducting a weight of sand equal to this excess, the ratio of fine aggregate to total aggregate combination was maintained at 37 percent by weight. Concrete placed in Experimental Section B was proportioned to contain 5 sk of cement and 140 lb of fly ash per cubic yard. The mixtures for Experimental Section B were proportioned in a manner similar to that used for Experimental Section A.

Materials were dry batched at a plant near the projects and were transported in dry-batch trucks to a Twinbatch mixer at the site. All batches were mixed for a 1-min period. The mixer was rated at 34 cu ft and was operated at a 10 percent overload, giving 37.4 cu ft per batch. All concrete was cured with wet burlap for a minimum of 3 days. Transverse and longitudinal joints were sawed within a 24-hr period after placement of the concrete. Joints were sawed to a depth equal to one-fourth the pavement depth.

Construction supervision and inspection were in accordance with standard departmental procedures for all construction projects. Division of Construction personnel made necessary adjustments in mixture proportions, sampled materials, supervised construction and provided necessary inspectors. Beams and cylinders were cast independently by research personnel for flexural and compressive strength testing at ages of 3, 7 and 28 days and 6 and 12 mo. Three-month compressive strength tests were also made on cylinders and freeze-thaw tests were conducted on 14-day-old beams. Each set of specimens cast consisted of 18 beams and 18 cylinders. All tests were in triplicate. Four such sets of specimens were cast from concrete placed in each of the three sections on the project.

All beams and cylinders were cast and cured in accordance with procedures outlined under ASTM Designation: C 31, Making and Curing Concrete Compression and Flexure Test Specimens in the Field. Compression test specimens, 6 in. in diameter and 12 in. in length, were cast. The specifications designate that coarse aggregate for specimens

TABLE 1

MIXTURE WEIGHTS PER CUBIC YARD—SLUMP AND AIR TEST RESULTS

Section	Date Placed	Material Weight (lb)[a]				Slump (in.)	Air Content (%)
		Free Water	S.S.D. Sand	S.S.D. Stone	Fly Ash		
Control	6-13-63	252.7	1,167	1,987	-	3, 2.5, 2, 2.5	5.2, 4.7, 4.8, 4.6
	7-17-63	264.2	1,156	1,970	-	2.5, 2.5, 2.25, 2.25	4.3, 4.5, 4.5, 4.6
	7-24-63	255.6	1,164	1,983	-	3, 2.5, 3, 3	4.7, 5.0, 4.8, 4.6
	8- 8-63	260.6	1,158	1,973	-	3, 3, 2.5, 3	2.3, 6.2, 6.2, 5.4
Avg.		258.3	1,161	1,978		2.64	4.7
Expr. A	12-5-62	238.9	1,175	2,012	94	2.5, 2.75, 2.5, 2.5	
	6-3-63	261.3	1,146	1,973	94	2, 2.25, 2.5, 2	3.7, 4.3, 4.1, 4.7
	6-11-63	253.4	1,138	1,983	94	3, 3, 2, 2.25, 2.25	6.2, 6.1, 5.0, 4.7, 4.9
	8-21-63	250.5	1,157	1,992	94	3, 3, 3, 2.75, 3	5.2, 4.8, 4.9, 4.7, 4.6
Avg.		258.3	1,161	1,978	94	2.56	4.8
Expr. B	7- 1-63	259.9	1,104	1,976	140	2, 2.25, 2.5, 2.25, 2.5	4.5, 4.9, 5.1, 4.7, 4.6
	7- 3-63	264.2	1,097	1,965	140	2.5, 2.75, 2, 2.25, 2.25	4.8, 4.5, 4.7, 5.0, 4.8
	7-15-63	259.9	1,104	1,974	140	3, 3, 2.5, 3	4.0, 6.5, 4.4, 4.7
	8- 1-63	257.0	1,107	1,978	140	3, 2.5, 2.25, 2.5, 2.5	2.8, 6.0, 4.9, 5.4, 5.6
Avg.		260.2	1,103	1,973	140	2.50	4.8

[a] Cement—564 lb for all control, 470 lb for all experiments.

TABLE 2

STRENGTH TEST DATA

Section	Date Placed	Free Water (lb/cu yd)	Compressive Strength[a] (psi)			Flexural Strength[a] (psi)		
			3 Day	7 Day	28 Day	3 Day	7 Day	28 Day
Control	6-13-63	252.7	3,249	3,806	4,914	806	850	1,050
	7-17-63	264.2	2,882	4,082	4,562	813	938	1,125
	7-24-63	255.6	2,963	4,073	5,453	725	956	1,075
	8- 8-63	260.6	3,447	3,776	4,949	735	1,062	1,263
Avg.		258.3	3,135	3,935	4,970	770	952	1,128
Expr. A	12- 5-62	238.9	1,958	3,872	4,868	385	813	1,106
	6- 3-63	261.3	2,952	3,570	4,619	738	988	1,188
	6-11-63	253.4	2,330	3,270	4,572	550	700	1,015
	8-21-63	250.5	2,896	3,759	4,551	738	900	1,012
Avg.		251.0	2,534	3,620	4,653	603	850	1,080
Expr. B	7- 1-63	259.9	2,855	3,349	5,208	719	863	1,138
	7- 3-63	264.2	2,445	4,124	5,496	687	925	1,275
	7-15-63	259.9	2,460	3,420	4,622	756	731	1,038
	8- 1-63	257.0	3,129	3,414	3,788	773	963	1,250
Avg.		260.2	2,727	3,577	4,799	734	871	1,175

[a] Average of three specimens.

of the size cast shall not exceed 2 in. in nominal size. To comply with that requirement, the fresh concrete used for casting all cylinders was passed through a 2-in. screen so as to eliminate stone greater than 2 in. in nominal size from the mixes. Flexure test specimens, 3- by 4- by 16-in., were cast and the fresh concrete used in the casting of these specimens was passed through a 1-in. screen to meet specification requirements.

RESULTS

The average free-water requirement for those mixtures from which beams and cylinders were cast were 30.99 gal/cu yd for the Control Section, 30.12 gal/cu yd for Experimental Section A, and 31.23 gal/cu yd for Experimental Section B. Slump and air-content tests were conducted four or five times per day during placement. Slumps ranged from 2 to 3 in. and averaged $2\frac{5}{8}$ in. Air contents ranged from 2.3 percent, an exceptional case, to 6.5 percent and averaged 4.78 percent. The quantity of air-entraining admixture required to entrain the desired percent of air was quite variable for mixtures placed within given sections, and no definite quantity of air-entraining agent to be added to mixtures for the various sections could be established. Table 1 gives weights of materials used in the various mixtures from which beams and cylinders were cast. Results of slump and air-content tests are included.

The fine aggregate used throughout the project was dredged river sand, somewhat deficient in fines. It was anticipated that sweetening of the mixtures in the experimental sections through the addition of fly ash would result in a reduction of the free-water requirement below that of the control mixtures. Tests on laboratory mixtures made before the start of construction indicated such a reduction in the free-water requirements for the experimental mixtures. The approximate free-water requirements for the laboratory mixtures were 31, 29, and 28.5 gal/cu yd, respectively, for the Control, Experimental A and Experimental B mixtures. However, no significant difference in free-water requirement was obtained in actual production of mixtures. In fact, the mixtures for Experimental Section B required slightly more water than those for the Control and Experimental A Sections.

The minimum expected strength of portland cement concrete for pavements as required by the Kentucky Department of Highways is 3,500 psi in compression and 600 psi, modulus of rupture, at 28 days. Specimens from all mixtures placed in the various sections met those designated minimum strength requirements. Strength test results for 3, 7, and 28 days on beams and cylinders cast and tested by Research Division personnel are listed in Table 2. Compressive and flexural strength tests were made in accordance with ASTM Designations: C 39-61 and C 293-59.

The average 3-mo compressive strength for cylinders cast on three various dates from concrete placed in Experimental Section A was 6,030 psi, the average for cylinders cast from concrete placed in Experimental Section B for the one date was 6,812 psi, and the average for cylinders cast from concrete placed in the Control Section for one date was 5,155 psi. Beams from all sections have shown excellent performance in freeze and thaw. Freeze and thaw tests were conducted in a manner similar to that outlined under ASTM Designation: C 310-61T.

CONCLUSIONS

Early strengths for concrete placed in the experimental sections were expected to be somewhat lower than that for the Control Section, unless a significant reduction in the water requirement could be achieved in the experimental sections. The reduction in the water requirement was not achieved, and the strengths through 28 days of concrete in the experimental sections were less than those for the control mixtures. This observation is in accordance with the general conception that pozzolanic benefits develop slowly and do not appear within the first month. On the basis of the limited 3-mo test data, the strengths for the experimental sections are higher than those of the Control, as was expected.

The major difficulty encountered during construction was in dispensing the correct amount of fly ash from the hopper at the batch plant. This problem was corrected by the installation of new rollers in the fly ash hopper. Finishers stated that concrete placed in the experimental sections had about the same finishing characteristics as that placed in the Control Section; however, occasional gumminess or stickiness was encountered when the concrete in the experimental sections was not finished immediately after placement. No definite requirements for the quantity of air-entraining admixture to be used in mixtures for various sections could be established because the quantity for various mixtures for a given section was quite variable.

Approximately 500 ft of pavement were placed in Experimental Section A on December 5, 1962. The temperature dropped below 32 F during the night and remained below freezing for several days thereafter. This section has been observed several times to date, and there is no indication of any detrimental effects therefrom. Extensive performance surveys are to be conducted periodically to evaluate all sections. Recommendations are forthcoming on completion of analysis of data from these performance surveys.