Use of Fly Ash in Concrete by the Alabama Highway Department

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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

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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

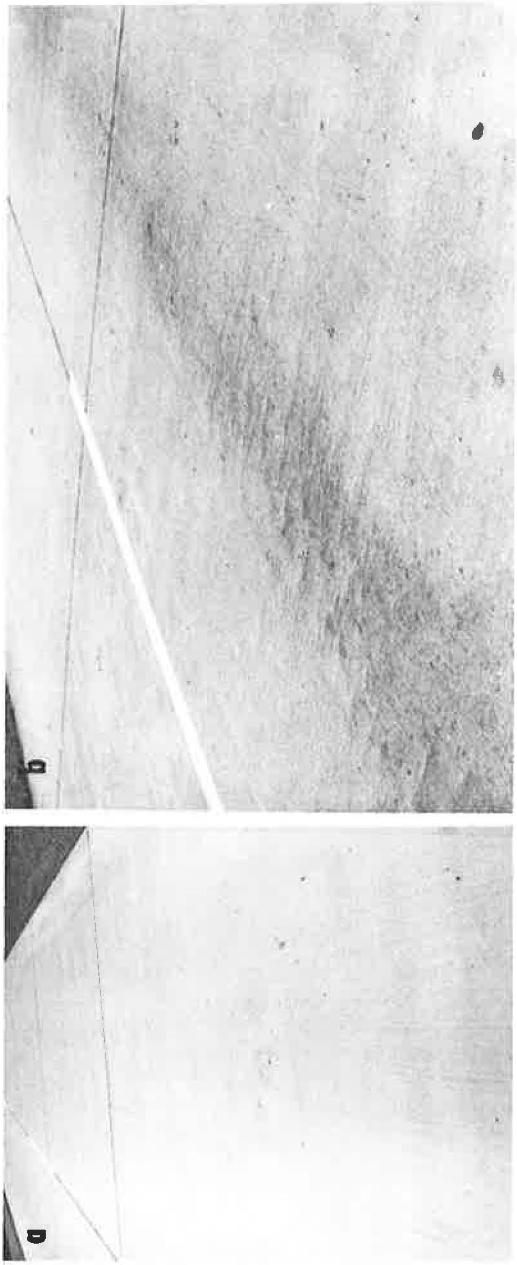

Figure 2. Concrete pavement: (a) with fly ash, and (b) without fly ash.

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 1½-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 1½-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 1½-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 1½-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 1½-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.

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