EVALUATION OF FLY ASH AS AN ADMIXTURE IN PORTLAND CEMENT CONCRETE

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ABSTRACT

The investigation of fly ash as an admixture in portland cement concrete (PCC) was divided into two phases. Phase I consisted of an experimental program while phase II involved an evaluation of fly ash concrete based on research reported by other agencies.

Data obtained in the experimental program provide evidence that both Class F and Class C fly ash can be used to manufacture concrete of comparable strength as that produced from conventional materials. In some cases fly ash concrete showed higher compressive strengths at both high and low cement factors depending on the fly ash source and its replacement ratio. The variable properties and characteristics often associated with fly ash and fly ash sources on the compressive strength of concrete cylinders were verified. Fly ash showed little effect on promoting expansion due to the alkali aggregate reaction, when used with a high alkali cement. The alkali content of fly ash may be more significant when used with a low alkali cement.

Research conducted by a wide variety of agencies lead to the conclusion that the addition of fly ash to PCC may cause a reduction in the water requirements of the mix, increased workability, reduced heat of hydration, increased time of set, reduced permeability, and lower early strength. Although much is still unclear concerning the effect of fly ash on the air void system and freeze thaw durability of concrete, some research has indicated that fly ash may actually improve durability, depending on fly ash type and replacement ratio.

Recommendations have been developed in this report for specifications, mix designs procedures, and testing of fly ash. Fly ash should conform

to ASTM C618 except for the modifications as listed in this report.

It is recommended that fly ash not be allowed in bridge decks, PCC pavements, or in prestressed concrete at this time. Further study should be undertaken to determine the feasibility of using fly ash in this manner. Except for seals, fly ash for use in substructure work, walks, curbs, barriers, other noncritical structures, and cement treated base (CTB) should be considered as a substitute for portland cement for a minimum of 10% to a maximum of 20% by weight of portland cement.

DISCLAIMER

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100 INTRODUCTION

The burning of finely ground coal in electrical generating power plants is increasing annually. As a result, the waste by-products emitted during the coal combustion process are growing as well. A large percentage of these by-products is fly ash.

110 Fly Ash

Fly ash is defined by American Society for Testing and Materials (ASTM) as the "finely divided residue that results from the combustion of ground or powdered coal." It falls under the broader heading of pozzolans. Pozzolans are defined by ASTM as "siliceous or siliceous and aluminous materials which in themselves possess little or no cementitious value but will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties." Fly ash is divided into 2 classes:

1. Class F - Normally produced from anthracite or bituminous coal and possesses pozzolanic properties.

2. Class C - Normally produced from lignite and sub-bituminous coal and in addition to pozzolanic properties has some cementitious properties due to its higher lime (expressed as CaO) content (2).

The primary constituents of fly ash are microscopic, predominantly spherical granules composed chiefly of oxides of silica, alumina, iron, and calcium. These granules are formed when small particles of clay, pyrite, and calcite from within the coal are exposed to temperatures in excess of 2700 F in the combustion chamber. During the combustion process about 75 to 80 percent of the ash will "fly" out of the combustion chamber with the flue gases, thus the name "fly ash." In modern plants nearly all the ash is recovered by electrostatic precipitators and fabric bag filters before the gas goes out the stack (15).

120 History

The use of pozzolan in the United States began with the initiation of reclamation programs and the development of hydroelectric power around 1910. Since 1940 the Bureau of Reclamation has regularly used pozzolans in its mass concrete (21). One of the first recorded uses of fly ash with portland cement was in 1936. Since that time, there have been numerous instances where fly ash has been used in portland cement concrete mixes. Until recently nearly all the published research and specifications involving fly ash were in reference to fly ash produced from bituminous coal. Consequently, the use of Class F fly ash as a partial replacement of portland cement is relatively well developed. Increased use of lignite and sub-bituminous coal, and the addition of limestone and dolomite injection processes to improve pollution control has resulted in the Class C fly ashes which are characterized by their higher calcium oxide and lower silicon oxide contents. The technology, however, for using Class C fly ash in portland cement concrete is still evolving (26).

In 1976 Congress passed the Resource Conservation and Recovery Act (RCRA) which requires that federal government agencies and state and local governments using federal money purchase products using recovered materials whenever feasible. The RCRA designated cement and concrete containing fly ash as a substance falling under the affirmative procurement requirements of the act. In January of 1983 the Environmental Protection Agency (EPA) published guidelines for federal procurement of cement and concrete containing fly ash. The EPA is of the opinion that the Federal-aid program for highway construction projects is subject to RCRA requirements (9). Although the Federal Highway Administration (FHWA) has not settled its differences with the EPA over the legal precedent which could be set by its interpretation of the Act, they are encouraging compliance with the guideline.

130 Objective

This study was undertaken to evaluate and better understand the characteristics of fly ash as an admixture in portland cement concrete, and to develop recommendations for its suitability and applications in Oregon construction projects. The evaluation was based on an experimental program conducted at the OSHD Engineering Laboratory and a review of available literature pertaining to fly ash concrete. Properties studied included durability, strength, time of set, and alkali-aggregate reaction of concrete containing fly ash. The experimental program was conducted over a 3 month period in the summer and fall of 1983 and involved compressive strength comparisons between fly ash and non-fly ash concrete batches. This program was followed by the literature review on the aforementioned properties of concrete.

200 USE OF FLY ASH CONCRETE (FAC) ON OSHD PROJECTS

Class F fly ash has been used as a partial replacement for portland cement on several OSHD projects through price agreement or by special provision. Most of the projects have been on the Interstate 205 freeway. In many cases, the use of fly ash resulted in savings to both the state and the contractor.

210 Projects

211 North Channel Structure (I205)

The Columbia River (I205) North Channel structure utilized fly ash in the columns up to the water level in order to reduce the heat of hydration. It resulted in a savings to the state of $41,300.

212 Airport Way Interchange & Columbia Slough Bridge (I205)

Fly ash was substituted for 15% of the cement by weight in all 3300 psi concrete (6.3 sacks of cement) on the Airport Way Interchange project at a rate of 1.25 to 1. The $1.34/cu. yd. savings was split equally among the state, contractor, and supplier. The Columbia Slough bridge also had a 15% reduction of cement for a $0.70/cu. yd. reduction in cost, of which the state received $0.38/cu. yd.

213 S.E. Powell-S.E. Foster & N.E. Failing-N.E. Hancock (I205)

Fly ash was used in the curbs on the S.E. Powell to S.E. Foster (I205) project at a savings to the state of $1.00/cu. yd.

Fly ash concrete was used in the 3300 psi-3/4" and 4000 psi-3/4" structural concrete mixes on the Failing St. to Hancock St. project after the Engineering Laboratory conducted a study. In this study 20 trial batches were produced with various cement factors, maximum size aggregate, and fly ash replacement levels. Data from the study is given in Table 1. It was found that for the 3300 psi-3/4" mix the fly ash batches at 7 and 28 days had lower compressive strengths than the batches without fly ash but had equal or greater strengths at 60 days. The 5000 psi-3/4" mix containing fly ash showed slightly lower strengths at every test age as did the 3300 psi 1-1/2" and 5000 psi 1-1/2" mixes. From this data it was recommended by the Materials Section that fly ash would be acceptable for the 3300 psi-3/4" and 4000 psi-3/4" mixes but would not be acceptable in the 1-1/2" maximum size aggregate mixes or the 5000 psi-3/4" mix.

214 Marion Street Bridge

Special provisions for the Marion Street bridge project allowed for the use of Class F fly ash as an option to replace 15% of the cement by weight on a 1.25:1 basis in all concrete except Class 4500-3/4". The contractor elected to use fly ash and from June, 1981 to September, 1981, 28 day compressive strengths varied from 2545 psi to 6155 psi and 3550 psi to 6860 psi for the Class 3300 and 4000 concrete respectively. Fly ash was not allowed after September because of low 28 day cylinder breaks. To determine if the low compressive strengths might be attributed to the colder initial curing temperatures, a study was conducted by the OSHD Engineering Laboratory of the effect of curing temperature on compressive strength at various ages for portland cement concrete and fly ash modified portland cement concrete mixes.

In this study three cylinders were cured for the first 24 hrs. at dif-

TABLE 1 - FAILING ST., - HANCOCK (626-1042)

FLY ASH INVESTIGATION

Sept., Oct., Nov., 1979

Date	Cement Reduction, %	Cement Reduction, lbs.	Cement Content	Fly Ash Content	Air %	Water, lbs/cy.	Slump in.	Compressive Strength 7 day	Compressive Strength 28 day	Compressive Strength 60 day
3/4" Max. 6.3 Sack Mix - 3300 psi										
9-04-79	-	-	589	-	5.2	263	3 1/2	3680	4850	5315
9-04-79	9	53	536	74	4.7	260	3 3/4	3490	4795	5380
9-05-79	14	82	507	112	4.8	252	3 3/4	3230	4455	5305
9-05-79	20	115	474	148	4.8	249	3 1/2	2905	4255	5190
9-12-79	14	81	508	131	4.8	246	3 1/2	3245	4650	5460
3/4" Max. 7.5 Sack Mix - 5000 psi										
9-06-79	-	-	702	-	5.6	280	3 3/4	3990	5020	5710
9-06-79	9	68	634	88	5.5	277	4	3515	4675	5310
9-11-79	14	97	605	134	5.2	265	3 1/2	3740	4940	5560
9-11-79	19	131	571	178	5.0	267	3 1/2	3480	4595	5405
9-12-79	14	98	604	156	4.9	266	4	3230	4985	5645
1½" Max. 6.3 Sack Mix - 3300 psi										
9-24-79	-	-	595	-	4.5	234	3 1/4	3225	4640	5230
9-24-79	10	58	537	75	4.5	235	3 3/4	2725	4030	4665
9-25-79	15	89	506	112	4.8	228	3 1/4	2480	3655	4320
9-25-79	20	117	478	149	4.7	226	3 1/4	2340	3430	4080
10-03-79	16	97	498	129	4.6	238	3 3/4	2495	3670	4450
1½" Max. 7.5 Sack Mix - 5000 psi										
9-27-79	-	-	712	-	4.5	262	3 1/2	3395	4530	5110
9-27-79	9	67	645	89	4.3	258	3 1/2	3060	4635	4980
10-02-79	16	112	600	133	4.7	257	3 1/2	2815	3820	4535
10-02-79	21	147	565	177	4.7	257	3 1/4	2575	3690	4365
10-03-79	16	114	598	155	4.5	255	3 3/4	2850	4240	4975

ferent temperatures (i.e. three @ 35 F, three @ 55 F, and three @ 75 F) and then placed in a standard moist room (@ 73.4 +/- 3 F) for the remainder of the curing period. Cylinders were tested at 7, 28 and 58 days for each of the curing temperatures. A tabulation of the results are given in Table 2. The study showed that lower initial curing temperatures resulted in higher ultimate compressive strengths for both the mixture with and without fly ash. It was concluded by the Lab that lower strengths for the fly ash mixes on the Marion St. Bridge were not a result of low curing temperatures.

A meaningful analysis of the wide variation in compressive strengths for the June 1981 to September 1981 period is not possible due to the lack of necessary data. Such a wide range of strengths is probably due to a variety of factors, which may include changes in the mix proportions used and lack of quality control, variations in the chemical and physical properties of the fly ash, curing temperatures, and handling and testing of FAC cylinders.

220 Discussion

Difficulties in obtaining the required design strengths of fly ash concrete have generally not been a significant problem on OSHD projects other than the one mentioned above. Although Class C fly ash from Boardman has been proposed by the contractor on a few projects, it has not been allowed. The main concern has centered around the high magnesium oxide (MgO) and alkali content (Na_2O equivalent) that has at times been found in this fly ash.

TABLE 2 - MARION STREET BRIDGE
FLY ASH INVESTIGATION

CONTROL MIXES

Mix Number	1	3	5	Ave.	Design
Portland Cement, lbs.	584	589	601	591	592
Fly Ash, lbs.	-	-	-	-	-
Water, lbs.	245	252	254	250	246
AEA, oz/sk.	1.0	0.8	0.5	0.77	-
Slump, inches	3 3/4	4½	4	4	3½ - 4½
Air Content, %	6.5	5.7	4.4	5.5	4.5 - 6.5
7 day psi @ 35°F	3530	3470	4020	3673	
@ 55°F	3340	3290	3630	3420	
@ 75°F	3230	3195	3730	3385	
28 day psi @ 35°F	5540	5510	5970	5673	
@ 55°F	4485	4670	5375	4843	
@ 75°F	4365	4520	5285	4723	
58 day psi @ 35°F	5820	5855	6195	5957	
@ 55°F	5080	5100	5765	5315	
@ 75°F	4740	5060	5640	5147	

TEST MIXES

Mix Number	2	4	6	Ave.	Design
Portland Cement, lbs.	506	504	497	502	503
Fly Ash, lbs.	112	111	110	111	111
Water, lbs.	243	235	236	238	240
AEA, oz/sk.	1.0	1.2	1.55	1.25	-
Slump, inches	4½	3 3/4	3 3/4	4	3½ - 4½
Air Content, %	4.8	5.4	6.6	5.6	4.5 - 6.5
7 day psi @ 35°F	3145	3050	2695	2963	
@ 55°F	2985	3030	2570	2862	
@ 75°F	3040	2830	2405	2762	
28 day psi @ 35°F	5320	4825	4640	4928	
@ 55°F	4645	4285	4090	4340	
@ 75°F	4415	4420	3705	4180	
58 day psi @ 35°F	5540	6245	5390	5725	
@ 55°F	5255	5035	4760	5017	
@ 75°F	5035	4760	4350	4715	

300 EXPERIMENTAL PROGRAM

Although fly ash has been used as a mineral admixture in concrete for over 40 years, only recently has any significant amount of research been done on the use of fly ash from Western sub-bituminous coals. It was felt that an experimental program using local fly ash, aggregate, and cement would give the most accurate evaluation of the merits of fly ash in concrete. Strength and durability of fly ash concrete were the properties of the greatest interest to Highway Division personnel. Therefore, compressive strength was the main criteria for comparison of fly ash and non-fly ash concrete. Durability was evaluated indirectly by the effects of freezing and thawing on compressive strength. A separate program investigated the effect of fly ash on the alkali-aggregate reaction. This section gives information on the testing procedures, materials, and batching and mixing procedures used in the experimental program, as well as a summary and discussion of data.

310 Testing Procedures

The evaluation of fly ash concrete was based on compressive strength of cylinders made and cured in the Engineering Laboratory according to ASTM C-192 and cylinders cured in cycles of freezing and thawing. All of the concrete batches made in the laboratory used a 3/4" maximum size aggregate. The concrete mix designs used were divided into 3 groups based on cement factors. Batches were made with cement factors of 4.5, 6.0, and 7.5 sacks of cement per cubic yard.

Each group contained at least one reference mix with no fly ash added and 5 mixes with fly ash. The reference mix had criteria for air content of 4 - 5%, slump of 3 1/2 - 4 1/2 in., and cement content of +/- 5 lbs. of the design cement content.

In each group, three of the mixes were designed for a 15% replacement of cement by weight with fly ash on a 1.25:1 basis, and the other two replaced 15% of the cement on a 1:1 basis. If the fly ash mixes did not come within 1/2%, 1/2 in., and +/- 5 lbs. of the reference mix on the air content, slump, and cement factor respectively, then the mix design was adjusted and only three 6 x 12 in. cylinders were cast for testing at 28 days. If the batch met the above criteria for slump, air content, and cement factor, then nine 6 x 12 in. cylinders were cast for compressive strengths at 7, 28, and 60 days. These cylinders were cured in accordance with ASTM C-192. In addition, three 3 x 6 in. cylinders were cast for the freeze thaw test.

The freeze thaw cylinders were cured in the moist room for 28 days, then were subjected to 8 hrs. of freezing at approximately 0 F and 16 hrs. of thawing in a water bath at approximately 70 F each working day for 28 calendar days. Specimens were stored in a frozen condition 2 days a week. The cylinders were tested for compressive strength (after 20 cycles of freezing and thawing) at 63 days after being cured in the moist room for an additional 7 days.

320 Materials

321 Aggregate

The coarse and fine aggregate used in this study was obtained from River Bend Sand & Gravel located in Salem, Oregon. The coarse aggregate was of igneous origin, primarily andesite. The sand was predominately silica. The coarse aggregate was recombined to meet the midpoint of the tolerance range of grading requirements for coarse aggregate in portland cement concrete, established by the 1974 edition of the OSHD Standard

Specifications. The fine aggregate was not recombined in the laboratory but was screened to assure compliance with the tolerance range set forth by the standard specifications. Gradation and other physical properties of the aggregate used are shown in Table 3.

322 Fly ash

Fly ash was obtained from 3 sources for use in the study. A Type F fly ash from a coal fired generating plant in Centralia, Washington and Type C fly ash from similar plants in Boardman, Oregon and Wheatland, Wyoming were received in sealed containers. The fly ash was kept sealed throughout the project to prevent an increase in moisture content due to the hygroscopic properties of fly ash. The fly ash was tested according to ASTM C311-77 'Sampling and testing fly ash or natural pozzolans for use as a mineral admixture in portland cement concrete.' A summary of the laboratory analysis is shown in Table 4.

323 Portland cement

Cement was obtained from the Oregon Portland Cement Co. at their Durkee plant. Care was taken to assure uniformity throughout the entire allotment. An Oregon Portland Type I - II low alkali cement was used in the project. Cement properties are shown in Table 5.

324 Air entraining agent

A wood resin, air entraining admixture was used in all concrete batches to assure compliance with the air content requirements set forth in this study. The admixture conformed to ASTM specifications for air entraining admixtures for concrete (C260-77). Laboratory results for the admixture are shown in Table 6.

TABLE 3 - AGGREGATE PHYSICAL PROPERTIES

Sieve Size Passing	Coarse Aggregate (3/4" - #4)	Fine Aggregate (#4 - 0)
	(Percent passing by weight of Total Aggregate)	
1	100	100
3/4	95	100
1/2	65	100
3/8	35	100
1/4	8	100
4	1	94
8	-	78
16	-	68
30	-	50
50	-	18
100	-	4
200	-	2.4
Dry rodded unit wt. (AASHTO T19)	107.7 lb/ft^3	-
Bulk specific gravity (SSD) (AASHTO T84, T85)	2.62	2.54
Absorption (AASHTO T84, T85)	2.40%	4.49%
OSHD Sand equivalent	-	74
Friable particles (AASHTO T112)	0.20%	1.8
Lightweight particles (AASHTO T113)	0.0%	0.0
Abrasion (AASHTO T96)	B - 12.98%	-
Soundness (AASHTO T104)	1.4%	6.2%

TABLE 4 - CHEMICAL AND PHYSICAL CHARACTERISTICS OF FLY ASH

	Centralia, WA Class F		Boardman, OR Class C		Wheatland, WY Class C	
	Test Sample	Specification (ASTM C618)	Test Sample	Specification (ASTM C618)	Test Sample	Specification (ASTM C618)
CHEMICAL COMPOSITION						
1) $SiO_2 + Al_2O_3 + Fe_2O_3$, min. %	77.7	70.0	62.0	50.0	72.7	50.0
2) Sulfur Trioxide, max. %	3.9	5.0	8.1	5.0	4.9	5.0
3) Moisture Content, max. %	0.07	3.0	0.1	3.0	0.1	3.0
4) Loss on Ignition, max. %	0.2	12.0	0.4	6.0	0.6	6.0
5) Magnesium Oxide (MgO), max. %	1.7	-	1.7	-	1.7	-
6) Available Alkalies, as Na_2O, max. %	0.95	1.50	1.1	1.50	0.97	1.50
PHYSICAL CHARACTERISTICS						
1) Amount retained on No. 325 sieve, max. %	9.3	34	10.7	34	11.2	34
2) Pozzolanic Activity Index						
a) With portland cement, @ 28 days, min. % of control	98	75	90	75	81	75
b) With lime, @ 7 days, min. psi	1385	800	1875	800	825	800
3) Water requirement, max. % of control	89.3	105	90.9	105	92.6	105
4) Autoclave expansion or contraction, max. % of control	0.02	0.8	0.02	0.8	0.008	0.8
5) Specific Gravity	2.47	-	2.60	-	2.63	-
6) Uniformity						
a) Specific gravity, max. variation from avg., %	-	5	-	5	-	5
b) Amount retained on No. 325 sieve, max. variation, % pts. from avg.	-	5	-	5	-	5
7) Multiple factor (loss on ignition x % ret. 325), max. %	1.8	255	4.1	-	7.1	-
8) Increase of drying shrinkage of mortar bars @ 28 days, max. %	-1.3	0.03	-0.66	0.03	-1.4	0.03
9) Quantity of AEA required to produce 18% in mortar, ml	1.37	-	0.95	-	1.71	-
a) Variation of quantity from avg., max. %	1.2	20	0.9	20	11.8	20
10) Reactivity with cement alkalies, mortar expansion @ 14 days, max. %	-	0.020	-	0.020	-	0.020

TABLE 5 - PORTLAND CEMENT ANALYSIS [a]

<u>Chemical Composition</u>

Silicon dioxide (SiO_2)	22.60%
Aluminum oxide (Al_2O_3)	3.25%
Ferric oxide (Fe_2O_3)	5.00%
Magnesium oxide (MgO)	1.01%
Sulfur trioxide (SO_3)	2.20%
Loss on ignition	1.00%
Insoluble residue	0.18%
Tricalcium silicate (C_3S)	54.60%
Tricalcium aluminate (C_3A)	0.20%
Total Alkalies (as Na_2O)	0.42%

<u>Physical Tests</u>

Fineness, Blaine	3780 cm^2/g
Setting time, Vicat	
Initial set	2 hrs. 10 mins.
Final set	4 hrs. 20 mins.
Compressive strength	
3 days	3050 psi
7 days	4175 psi

[a] Type I and II L.A. portland cement

TABLE 6 - AIR ENTRAINING ADMIXTURE ANALYSIS

Air Content of Hydraulic Cement Mortar (Mortar with the addition of 0.365 g admixture, % by volume), AASHTO T137	20.1
Chloride Content (Percent chlorides by weight, as chloride ion)	0.022
Specific Gravity	1.015
pH	12.26

330 Batching & Mixing Procedures

The amount of oven dried coarse aggregate corresponding to the dry weight required from the mix design was weighed in plastic buckets and allowed to soak for 24 hours prior to use. The weight and gradation of the coarse aggregate was kept constant throughout the project. The aggregate was placed in the mixer after draining the excess water and determining the moisture content. Surface moisture was included in the amount of mixing water used. The fine aggregate was then placed in the mixer at a known moisture content above the absorption factor and the surface moisture was included in the amount of mixing water used. Half of the calculated amount of mixing water required, determined from the design, was then placed with the coarse and fine aggregate along with the air entraining agent and was premixed for approximately 30 seconds. Cement and fly ash (if applicable) were then placed in the mixer along with the rest of the mixing water. After all the ingredients were in the mixer, the batch was mixed for 3 minutes, followed by a 3 minute rest, followed by 2 minutes of final mixing.

Immediately after mixing, the slump was measured in accordance with ASTM T143 and the air content was determined according to ASTM C231. A yield test was performed in accordance with ASTM C138. The 6 x 12 in. cylinders were cast in tin molds in accordance with ASTM C192 and the 3 x 6 in. freeze-thaw cylinders were cast in paper molds.

340 Discussion of Data

A summary of the data collected during the experimental program is shown in Table 7. Table 8 is condensed from Table 7 and shows only data pertinent to evaluating the fly ash mixes. This table also shows the

TABLE 7a - CONCRETE DATA FOR THE 4.5 SACK MIX

	Batch Number						
	1	2	3	4	5	6	7
Date Cast	8/17	8/18	8/18	8/18	8/22	8/22	8/23
Design Information							
Cement Content (lb/yd^3)	423	359	359	359	359	359	359
Fly Ash Source	Ref.	CNTRL	BRDMN	LRME	LRME	BRDMN	LRME
Replacement Ratio	-	1.25:1	1.25:1	1.25:1	1.25:1	1:1	1:1
Batch Weights							
Cement (lb.)	32.23	27.40	27.40	27.40	27.40	27.40	27.40
Fly Ash (lb.)	None	6.04	6.04	6.04	6.04	4.83	4.83
Fine Aggregate (lb.)	101.60	98.78	99.09	98.72	99.89	101.03	100.84
Coarse Aggregate (lb.)	150.10	152.79	151.63	150.70	154.63	150.90	150.C8
Air Ent. Agent (oz/sk.)	0.78	0.86	0.92	0.89	0.93	0.92	1.08
Mixing Water (lb.)	18.56	16.93	16.74	17.44	17.16	17.53	17.78
Moisture Content of Aggregate							
Fine Aggregate (%)	5.08	5.83	5.83	5.36	6.61	6.61	6.35
Coarse Aggregate (%)	4.24	6.10	5.30	4.65	7.38	4.79	4.78
Properties of Fresh Concrete							
Unit Weight (lb/ft^3)	143.3	142.7	142.4	145.5	144.4	143.5	142.1
Cement Content (lb/yd^3)	416.7	357.4	356.5	363.3	361.0	358.4	354.6
Air (%)	4.6	5.0	5.3	3.4	4.3	4.6	5.2
Slump (in.)	3.75	3.50	4.50	3.25	3.25	3.75	4.25
Compressive Strength of Standard Moist Cured Cylinders (Avg. of 3)							
@ 7 days (psi)	1307	1380	1057	-	1565	1398	1333
@ 28 days (psi)	2870	2508	1980	2638	2982	2752	2553
@ 60 days (psi)	3490	3240	2773	-	3857	3523	3498
Compressive Strength of Freeze-Thaw Cylinders (Avg. of 3)							
@ 63 days (psi)	2783	2440	2392	-	3070	2670	4313

TABLE 7b - CONCRETE DATA FOR THE 6.0 SACK MIX

	Batch Number										
	8	9	10	11	12	13	14	15	16	17	18
Date Cast	8/2	8/3	8/3	8/4	8/4	8/8	8/8	8/8	8/16	8/16	8/17
Design Information											
Cement Content (lb/yd^3)	564	564	564	479	479	479	479	479	479	479	479
Fly Ash Source	Ref.	Ref.	Ref.	CNTRL	CNTRL	BRDMN	BRDMN	LRME	BRDMN	BRDMN	LRME
Replacement Ratio	-	-	-	1.25:1	1.25:1	1.25:1	1.25:1	1.25:1	1:1	1:1	1:1
Batch Weights											
Cement (lb.)	42.97	42.97	42.97	36.53	36.53	36.53	36.53	36.53	36.53	36.53	36.53
Fly Ash (lb.)	None	None	None	8.08	8.08	8.08	8.08	8.06	6.48	6.48	6.48
Fine Aggregate (lb.)	89.23	91.86	92.09	87.96	88.83	88.40	88.23	88.27	89.91	89.57	88.71
Coarse Aggregate (lb.)	152.81	154.32	154.10	151.86	153.49	151.94	156.33	154.37	151.41	151.81	151.70
Air Ent. Agent (oz/sk.)	0.75	0.78	0.70	0.91	0.91	0.91	0.96	0.96	0.96	1.04	1.07
Mixing Water (lb.)	21.45	18.71	19.21	18.21	18.09	18.21	17.64	17.54	19.43	18.47	18.49
Moisture Content of Aggregate											
Fine Aggregate (%)	7.05	6.79	7.06	6.61	7.15	6.60	6.39	6.39	6.60	6.37	5.08
Coarse Aggregate (%)	6.12	7.17	7.01	5.46	6.59	5.51	8.56	7.20	5.15	5.42	5.35
Properties of Fresh Concrete											
Unit Weight (lb/ft^3)	142.4	144.7	145.9	143.4	146.3	146.9	144.8	145.3	146.0	144.9	144.6
Cement Content (lb/yd^3)	552.9	561.6	565.2	477.1	486.1	487.8	482.0	483.6	483.0	481.4	479.8
Air (%)	5.2	4.2	3.5	5.0	3.5	3.4	4.3	3.9	3.5	4.2	4.3
Slump (in.)	8.0	4.0	3.25	4.5	3.25	3.5	4.0	4.75	4.0	4.0	3.75
Compressive Strength of Standard Moist Cured Cylinders (Avg. of 3)											
@ 7 days (psi)	-	2620	-	2195	-	-	2245	2123	-	2560	2132
@ 28 days (psi)	3638	3987	4178	3662	4427	4373	4372	4670	4427	4240	4073
@ 60 days (psi)	-	5415	-	4616	-	-	4505	4302	-	5347	4553
Compressive Strength of Freeze-Thaw Cylinders (Avg. of 3)											
@ 63 days (psi)	3258	4280	4103	3979	5403	-	3775	3868	-	3992	3488

TABLE 7c - CONCRETE DATA FOR THE 7.5 SACK MIX

	Batch Number										
	19	20	21	22	23	24	25	26	27	28	29
Date Cast	8/23	8/23	8/29	8/31	8/31	8/24	8/25	8/25	8/26	8/26	8/29
Design Information											
Cement Content (lb/yd^3)	705	705	705	705	705	599	599	599	599	599	599
Fly Ash Source	Ref.	Ref.	Ref.	Ref.	Ref.	CNTRL	CNTRL	BRDMN	LRME	BRDMN	LRME
Replacement Ratio	-	-	-	-	-	1.25:1	1.25:1	1.25:1	1.25:1	1:1	1:1
Batch Weights											
Cement (lb.)	56.24	56.24	55.50	55.50	55.50	47.18	47.18	47.18	47.18	47.18	47.18
Fly Ash (lb.)	None	None	None	None	None	10.55	10.55	10.55	10.55	8.46	8.46
Fine Aggregate (lb.)	83.87	85.41	86.15	84.47	84.47	83.28	83.28	84.67	82.71	84.70	87.02
Coarse Aggregate (lb.)	150.01	155.34	150.93	151.78	150.60	151.12	151.15	150.95	150.87	151.39	151.04
Air Ent. Agent (oz/sk.)	0.77	0.81	0.79	0.83	1.15	1.01	1.21	1.35	1.68	1.55	1.82
Mixing Water (lb.)	21.58	22.49	22.04	21.61	21.41	21.14	21.37	23.27	20.94	20.74	20.80
Moisture Content of Aggregate											
Fine Aggregate (%)	6.35	6.35	8.42	6.31	6.31	7.67	7.67	8.49	5.85	5.85	8.42
Coarse Aggregate (%)	4.17	7.88	4.81	5.40	4.58	4.94	4.97	4.83	4.77	5.13	4.89
Properties of Fresh Concrete											
Unit Weight (lb/ft^3)	145.5	144.6	146.1	145.1	144.4	145.2	144.3	145.5	145.3	145.0	143.5
Cement Content (lb/yd^3)	718.3	708.1	710.8	706.9	703.6	602.0	598.1	599.4	601.6	600.7	594.1
Air (%)	3.5	5.1	3.2	3.5	4.0	3.5	4.2	3.5	3.7	3.8	4.5
Slump (in.)	3.75	4.75	4.25	4.25	4.25	4.0	4.25	3.75	3.75	3.5	4.0
Compressive Strength of Standard Moist Cured Cylinders (Avg. of 3)											
@ 7 days (psi)	-	3233	-	3392	3087	-	2880	3248	3130	3185	2678
@ 28 days (psi)	5002	5020	4868	5297	4702	4215	4377	4663	4753	4652	4167
@ 60 days (psi)	-	5173	-	5363	5188	-	5245	5172	5562	5413	4598
Compressive Strength of Freeze-Thaw Cylinders (Avg. of 3)											
@ 63 days (psi)	-	2247	-	4500	4083	-	3898	4960	5438	4653	3888

TABLE 8 - CONCRETE DATA SUMMARY SHEET

Batch No.	Design Cement (Sks. Yd^3)	Cement Content (Lb/Yd^3)	Fly Ash Source	Repl. Ratio	Air (%)	Slump (in.)	(Compressive Strength/Standard Deviation)[a] (Standard Moist Cured Cylinders) @ 7 days	@ 28 days	@ 60 days	Freeze/Thaw Cylinders @ 63 days
1	4.5	416.7	Reference	-	4.6	3.75	1307/ 58	2870/105	3490/396	3258/145
2	4.5	357.4	Centralia	1.25:1	5.0	3.5	1380/ 15	2508/ 49	3240/212	4280/316
3	4.5	356.5	Boardman	1.25:1	5.3	4.5	1057/ 13	1980/ 55	2773/ 95	4103/353
4	4.5	363.3	Laramie	1.25:1	3.4	3.25	-	2638/ 14	-	-
5	4.5	361.0	Laramie	1.25:1	4.3	3.25	1565/ 23	2982/ 53	3857/162	3303/1223
6	4.5	358.4	Boardman	1:1	4.6	3.75	1398/ 38	2752/ 14	3523/ 41	5403/305
7	4.5	354.6	Laramie	1:1	5.2	4.25	1333/ 33	2553/ 55	3498/ 73	3775/149
8	6.0	552.9	Reference	-	5.2	8.0	-	3638/228	-	3867/855
9	6.0	561.6	Reference	-	4.2	4.0	2720/173	3987/525	5415/193	3992/313
10	6.0	565.2	Reference	-	3.5	3.25	-	4178/205	-	3488/110
11	6.0	477.1	Centralia	1.25:1	5.0	4.5	2195/130	3662/266	4617/276	2783/302
12	6.0	486.1	Centralia	1.25:1	3.5	3.25	-	4427/ 80	-	2440/231
13	6.0	487.8	Boardman	1.25:1	3.4	3.5	-	4373/ 63	-	-
14	6.0	482.0	Boardman	1.25:1	4.3	4.0	2245/ 84	4372/ 99	4505/238	2392/120
15	6.0	483.6	Laramie	1.25:1	3.9	4.75	2123/ 40	4670/ 44	4302/ 84	3070/241
16	6.0	483.0	Boardman	1:1	3.5	4.0	-	4427/ 35	-	-
17	6.0	481.4	Boardman	1:1	4.2	4.0	2560/ 58	4240/101	5347/ 70	2670/ 88
18	6.0	479.8	Laramie	1:1	4.3	3.75	2132/ 94	4073/ 73	4553/184	4313/525
19	7.5	718.3	Reference	-	3.5	3.75	-	5002/ 58	-	-
20	7.5	708.1	Reference	-	5.1	4.75	3233/162	5020/ 13	5173/ 59	2247/140
21	7.5	706.9	Reference	-	3.5	4.25	3392/ 18	5297/ 28	5363/110	-
22	7.5	703.6	Reference	-	4.0	4.25	3087/183	4702/319	5188/652	3898/345
23	7.5	710.8	Reference	-	3.2	4.25	-	4868/174	-	4960/217
24	7.5	602.0	Centralia	1.25:1	3.5	4.0	-	4215/136	-	-
25	7.5	598.1	Centralia	1.25:1	4.2	4.25	2880/ 96	4377/101	5245/176	5438/157
26	7.5	599.4	Boardman	1.25:1	3.5	3.75	3248/221	4663/ 26	5172/ 95	4653/ 53
27	7.5	601.6	Laramie	1.25:1	3.7	3.75	3130/ 53	4753/116	5562/ 34	3888/407
28	7.5	600.7	Boardman	1:1	3.8	3.5	3185/ 48	4652/ 68	5413/ 71	4500/429
29	7.5	594.1	Laramie	1:1	4.5	4.0	2678/ 46	4167/ 45	4598/108	4083/ 83

[a] Compressive strength and standard deviation given in psi.

average compressive strengths and their standard deviations. Figure 1 gives a graphical comparison of compressive strength at various ages. The comparison of compressive strengths for fly ash and non-fly ash mixes was divided according to the number of sacks of cement per cubic yard used in the batch.

As can be seen from Table 8, only batch number 3 showed lower compressive strengths for the moist cured cylinders at every age than the reference mix for the Class 2000 (4.5 sacks/cu. yd.) concrete. Its low strengths can possibly be explained by the high air content and slump associated with this batch. This batch was one of three that varied slightly with the criteria previously set forth regarding conformity of cement factor, air content, and slump with the reference mix. Batch numbers 11 and 27 were the other two batches that varied slightly from their control mix. These batches were not remade due to a shortage of the original sample of materials. Compressive strengths for batch numbers 6 and 7 were lower than the reference at 28 days but higher again at 60 days. Lower strengths for batch number 7 may be due to its higher slump and air content. Batch number 2 had slightly lower strengths at 28 and 60 days but this also could be due to its higher air content.

Batch number 4 had a lower strength at 28 days than batch number 5 even though batch number 4 had a higher cement content, lower air content, and lower slump than this batch. This gives a good illustration of the variability in compressive strengths often associated with Portland Cement Concrete (PCC) batches. All told, fly ash showed very favorable results at this lower cement factor. Not only in comparison with the reference mix, but also in terms of the 4.5 sack mix in general, which is used for the design of 2000 psi concrete.

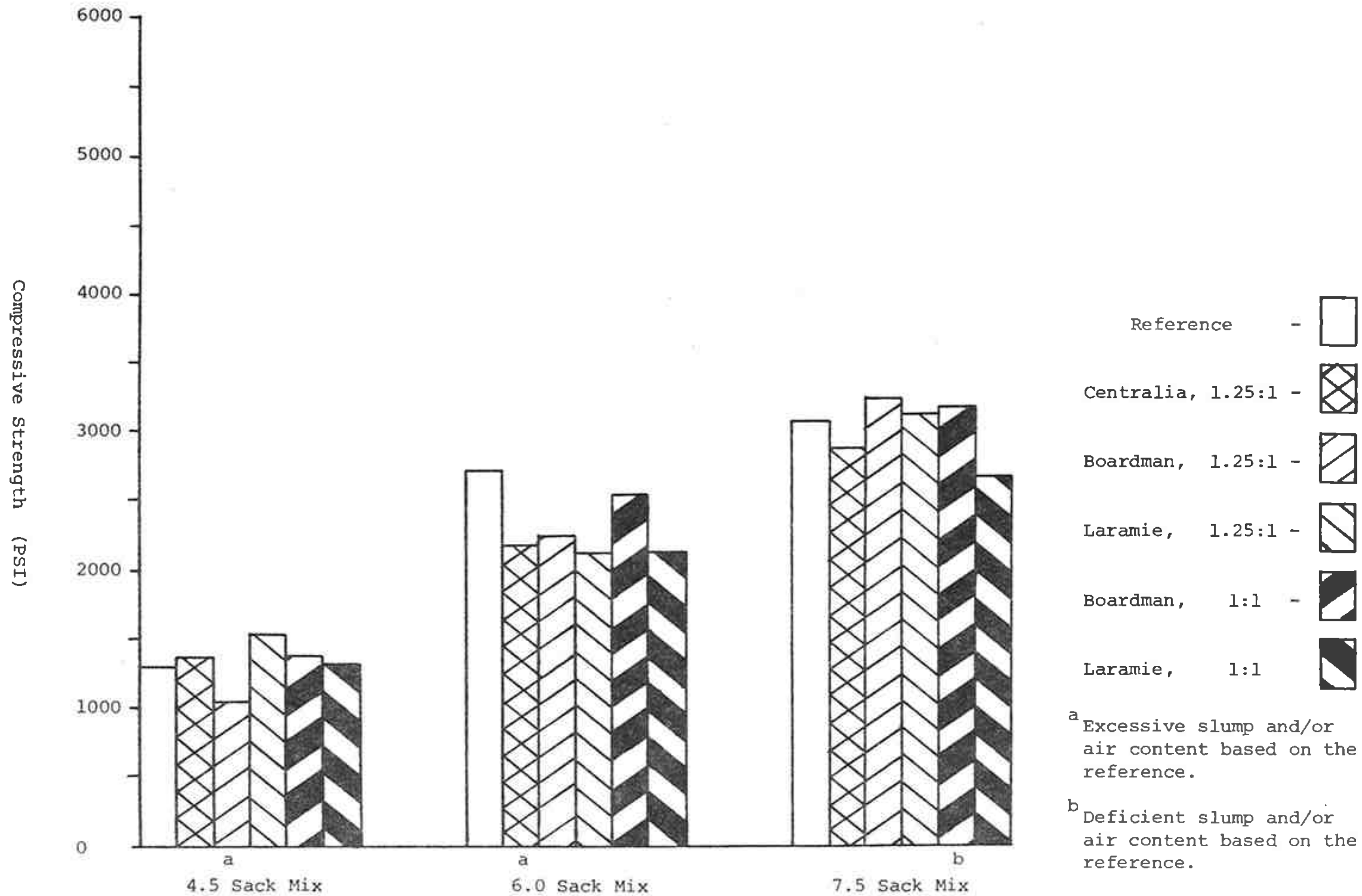

Figure 1a - Comparison of compressive strengths at 7 days of concretes with and without fly ash.

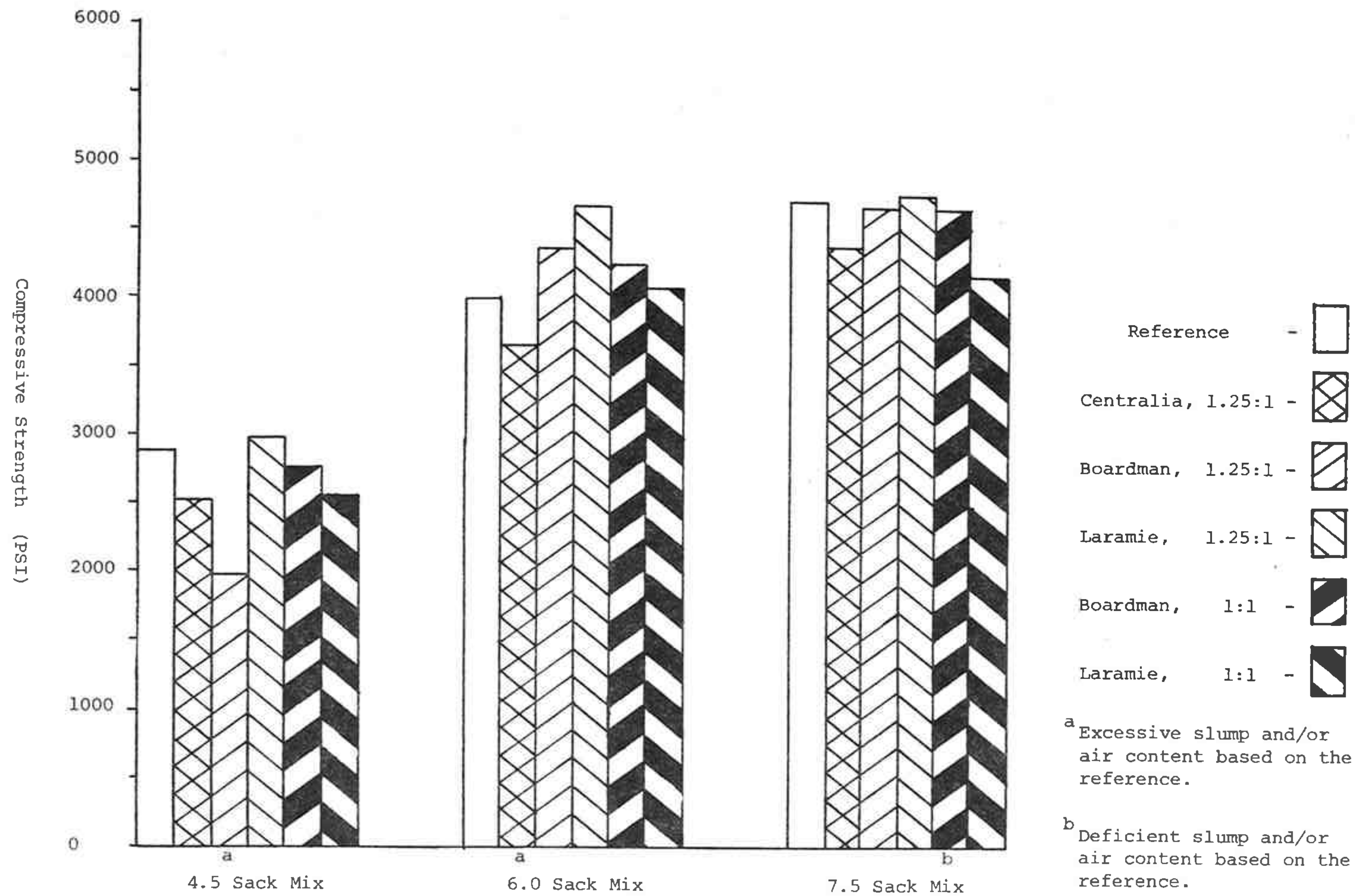

Figure 1b - Comparison of compressive strengths at 28 days of concretes with and without fly ash.

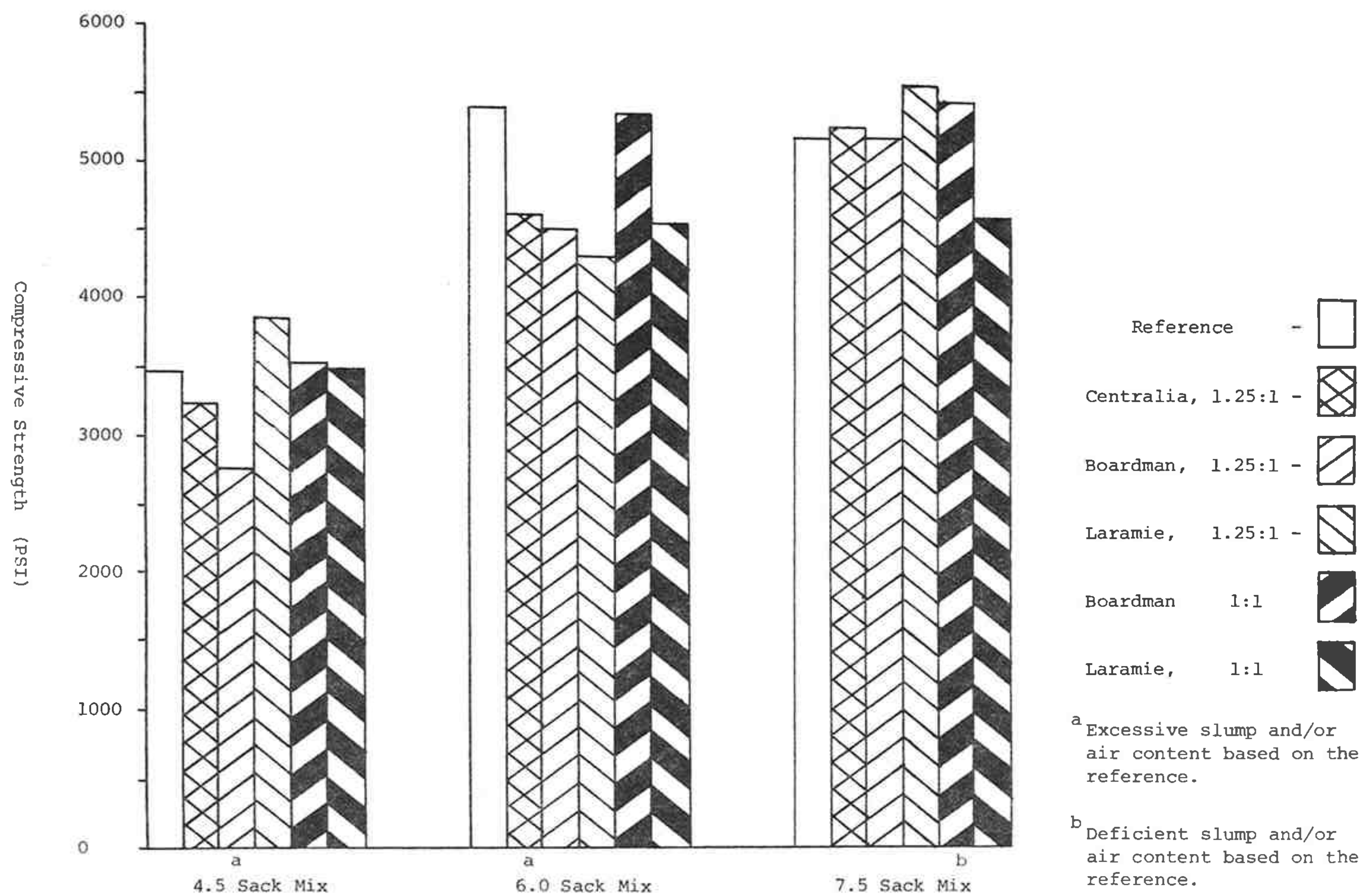

Figure 1c - Comparison of compressive strengths at 60 days of concretes with and without fly ash.

Fly ash strengths at 28 days for the Class 3300 (6 sacks/cu. yd.) were higher than the reference in every case except batch number 11 (already noted). But, the strength comparison at 60 days was lower for fly ash batches than the reference batch. Of the fly ash mixes, only batches 11, 17, 18 showed any significant strength increase due to the extra curing time. This poor showing of ultimate strength in connection with the reference mix is contrary to prediction where, an attribute of fly ash is its greater ultimate strength in almost all cases. It should be noted that all of the fly ash batches had compressive strengths in excess of the 3300 psi requirement. The Class 3300 reference mix attained higher ultimate strength than any of the Class 5000 control mixes, indicating an unusually high strength reference batch.

Compressive strengths for the Class 5000 (7.5 sacks/cu. yd.) were more in conformance with the expected results. In general, fly ash concrete strengths were lower at 28 days but equal or greater than the control at 60 days. Neither the reference mix nor any of the fly ash batches met the requirements (5000 psi) associated with this cement factor. However, the use of a water reducing chemical admixture is sometimes necessary to attain this desired strength.

On the basis of the mean compressive strengths given in Table 8, it is difficult to compare individual types of fly ash or their cement replacement ratios. The Class C ash from Boardman at a 1:1 ratio was comparable in strength to the same ash at a ratio of 1:25:1. Also, the Boardman ash showed better results than the Laramie at the 1:1 replacement level. The Class F (Centralia) fly ash was comparable to Class C at either a 1.25:1 or 1:1 ratio, except at the 4.5 sack class, where it gave slightly lower strengths.

It can be inferred from the data that no fly ash or cement replacement ratio is the most effective in all cases. However, satisfactory results meeting the OSHD standard specifications for compressive strength can be obtained with the use of fly ash concrete. Improvement in strength could be expected by adjusting the mix designs to determine the optimum amounts of coarse and fine aggregates and fly ash replacement ratios at each class, as well as the incorporation of chemical admixtures.

350 Freeze-Thaw Test

Compressive strengths from the 3 x 6 in. cylinders subjected to 20 cycles of the freeze thaw test are shown in Table 8. In general, the cylinders containing fly ash gave higher compressive strengths at the 4.5 sack cement factor. Compressive strengths for the reference mix for the 6.0 sack cement factor were higher than the fly ash mixes in every case but one.

Although there is a correlation between durability and compressive strength it is not a complete one and the data does not necessarily show that fly ash concrete has lower freeze-thaw durability at higher cement factors. Also, the specimens were tested after only 20 cycles of freezing and thawing which may not have been enough to initiate degradation. A better evaluation of the freeze-thaw durability characteristics of fly ash concrete would have been achieved by performing ASTM C666 'Resistance of Concrete to Rapid Freezing and Thawing.' In this test the samples are subjected to 300 cycles of freezing and thawing and measurement of fundamental transverse frequency is used to determine a durability factor. This test was not conducted due to the lack of necessary equipment.

360 Alkali-Aggregate Test

The investigation concerning the effect of fly ash on the alkali-aggregate reaction was separated into two phases. Tests were performed in accordance with ASTM C441-81 "Effectiveness of mineral admixtures in preventing excessive expansion of concrete due to the alkali-aggregate reaction." In Phase I three different fly ashes were tested with high alkali (1.17% available alkalies) cement, while in Phase II a low alkali cement was tested with just one fly ash sample. The mortar bars were constructed with crushed pyrex glass (a highly reactive aggregate) and increase in expansion was measured after 14 days. Both phases had one set of mortar bars containing cement, glass, and water by which the bars containing fly ash were compared. Table 9 shows the percent expansion and reduction in mortar expansion on each set. The results show that fly ash reduced expansion of mortars containing a high alkali cement and reactive aggregate. The fly ash used in Set IIA was not as effective as the other fly ash samples which may be due to the higher alkali content (1.46% available alkalies) associated with this material. This same fly ash when tested with the low alkali cement (IIB) had expansions significantly greater than the control (IB). To what degree this expansion is considered harmful is not known. It should be pointed out that pyrex glass is a very highly reactive aggregate. Aggregates found in Western Oregon are considered to be nonreactive.

TABLE 9 - ALKALI - AGGREGATE EXPANSION

Phase I

Set Number	Materials	Average[a] Expansion, %	Reduction in Mortar Expansion, %
I A	400 g - cement[b] 900 g - glass 176 ml - water 112½ - flow	0.343	NA
II A	300 g - cement[b] 88 g - fly ash[c] 900 g - glass 165 ml - water 114½ - flow	0.250	27.1
III A	300 g - cement[b] 78.4 g - fly ash[d] 900 g - glass 160 ml - water 108½ - flow	0.150	56.3
IV A	300 g - cement[b] 82.5 g - fly ash[e] 900 g - glass 162 ml - water 107½ - flow	0.161	53.1
	Phase II		
I B	400 g - cement[f] 900 g - glass 184 ml - water 102 - flow	0.003	NA
II B	300 g - cement[f] 88 g - fly ash[c] 900 g - glass 171 ml - water 101 - flow	0.156	- 5100

[a]Set of 3 mortar bars

[b]High alkali cement (1.17% available alkalies)

[c]Boardman fly ash (1.46% available alkalies)

[d]Centralia fly ash (0.95% available alkalies)

[e]Laramie fly ash (0.97% available alkalies)

[f]Low alkali cement

400 EVALUATION OF FLY ASH CONCRETE

Because there were several areas requiring investigation which were beyond the scope of the experimental program, an evaluation of certain characteristics of FAC was made by utilizing applicable reports by outside agencies. This section includes information concerning the effect of FAC on alkali-aggregate reaction, freeze-thaw durability, sulfate resistance, heat of hydration, time of set, and water requirements

410 Alkali-Aggregate Reaction

Certain reactive forms of silica can produce deleterious chemical reactions with the alkalies that are released during the hydration of portland cement which may cause expansion and cracking in concrete (14). This expansion known as the alkali-aggregate reaction can be reduced or eliminated by using low alkali cement (below 0.6% available alkalies), using nonreactive aggregates, and/or incorporating certain amounts of selected pozzolans (8).

Some research has shown that the addition of fly ash to concrete may reduce the alkali-aggregate expansion due to the finely powdered reactive silica in the fly ash (8). Since the silica in fly ash can react with the alkalies in the cement, this is contrary to expectation. This apparent paradox can be explained by Fig. 2. With low silica content an increase in silica for the same amount of alkalies will increase expansion, but with higher silica content the situation is reversed. Fig. 3 extracted from Porter's report (23), corresponds with these findings.

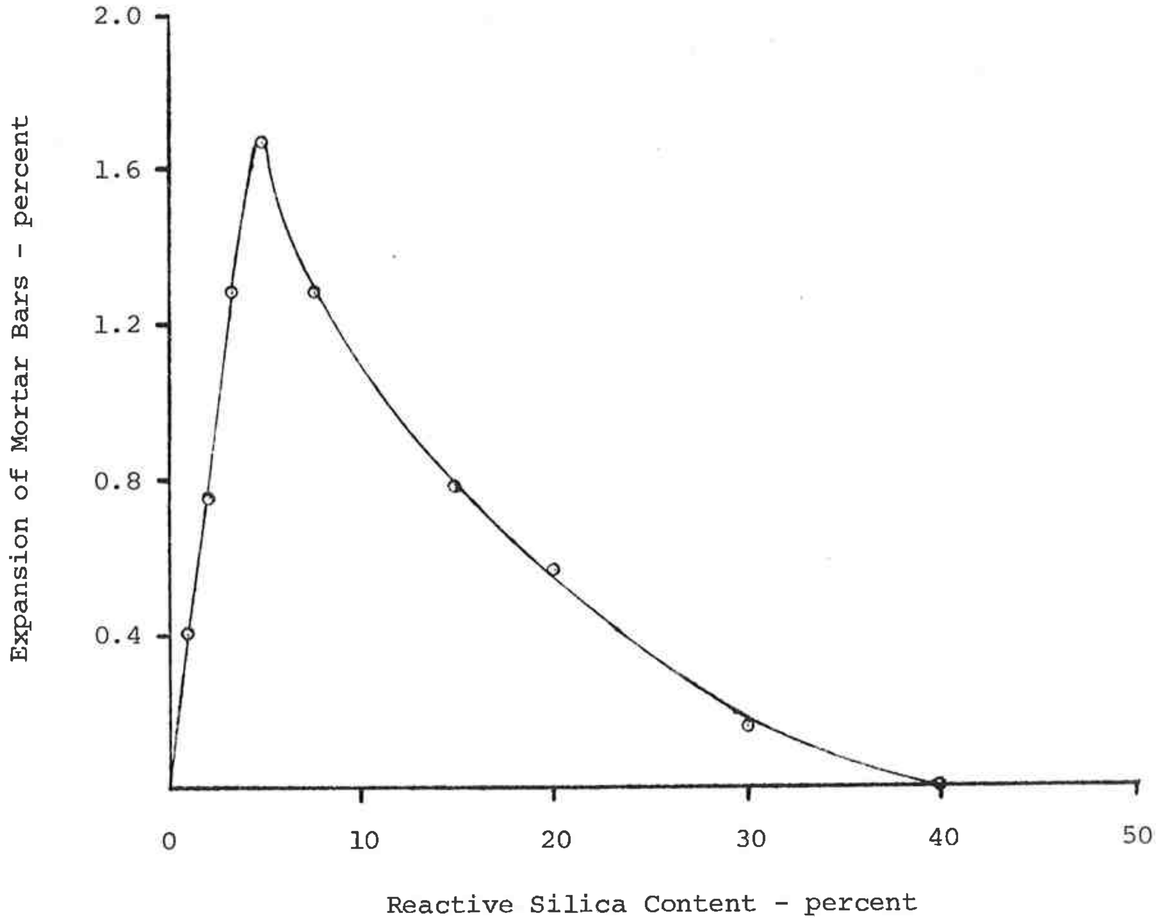

Fig. 2 - Relation between expansion after 224 days and reactive silica content in the aggregate (8).

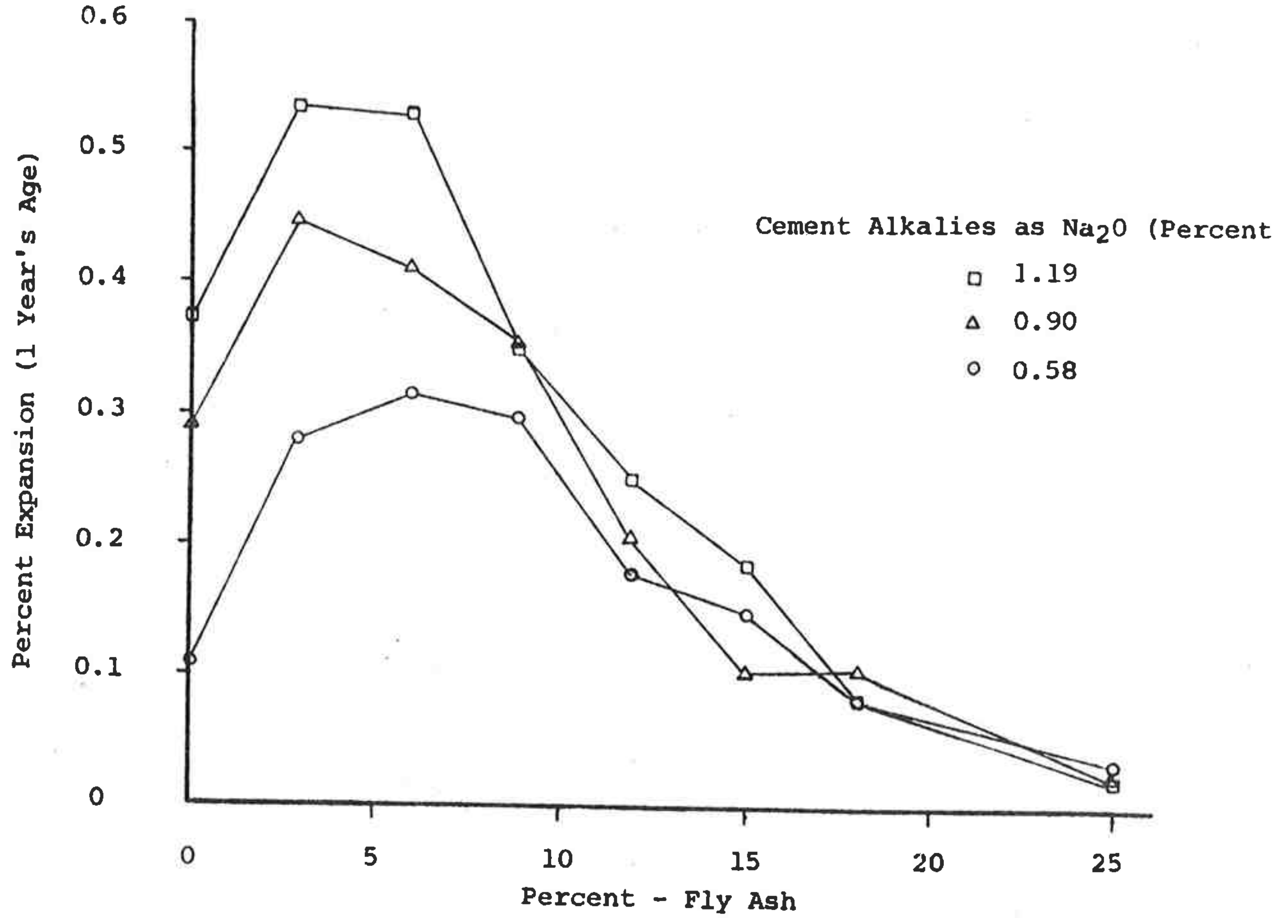

Fig. 3 - Effect of cement alkalies and fly ash replacement percentage on alkali-aggregate reaction (24).

The greater the surface area of the reactive aggregate the lower the quantity of alkalies available per unit of this area, and the less alkali-silica gel can be formed (18). On the other hand, in order for alkali to attack the siliceous material and form a swelling alkali-silica gel, it must compete with calcium hydroxide which can also react with the aggregate and form a nonswelling innocuous compound. The calcium ion is not nearly as mobile as the alkali ion and is therefore only available at the surface of the aggregate (i.e. the alkali ion can move to the aggregate from some distance away). Thus, increasing the surface area increases the calcium hydroxide/alkali ratio of the solution at the boundary of the aggregate. In which case the nonexpanding calcium alkali silicate product is formed (14).

With high alkali cement it seems evident that the chemical composition of fly ash is able to overcome the effect of its own alkalies, and to compensate for the deleterious effect of the alkalies in the cement (1). The effect of the alkalies in fly ash when used with a low alkali cement is not well understood. Dunstan (8) tested several fly ash samples with a high alkali cement and found that fly ash reduced expansion over the portland cement control mortars. He did no tests with a low alkali cement but suggested that the alkali content of fly ash may be more significant with these cements. This agrees with the one set of test results reported in the experimental program. More work needs to be done in this area.

420 Freeze-Thaw Durability

The incorporation of air entrainment in portland cement concrete has long been recognized as a necessary means of increasing its resistance to repeated cycles of freezing and thawing. In air-entrained concrete the air exists as extremely small bubbles well distributed throughout the cement paste. These small air bubbles are difficult to fill with water, but when water is expelled from the larger air cavities, the small air bubbles provide additional space to reduce the hydraulic pressures developed as free water is converted to ice during freezing. The closer the spacing of the air bubbles, the less hydraulic pressure generated and the less damage to the concrete (14, 26).

The internal air void system is usually described quantitatively in terms of the spacing factor or the specific surface. The spacing factor is the maximum distance of any point in the cement paste from the edge of an air void. The specific surface is the area of the air voids per unit volume. An ideal entrained air system would have a small spacing factor and a large specific surface (14, 26). The effect of fly ash on not only the air content, but also the air void system in the hardened concrete is of interest.

It is generally well accepted that the addition of fly ash to concrete will increase the required amount of air entraining agent (AEA) necessary to yield the same air content as concrete without fly ash. This is due primarily to the carbon content (measured by the loss on ignition test) of the fly ash. The highly surface active carbon particles act to absorb the organic air entraining agents (25). AEA dosage rates for fly ash concrete cylinders cast in the Engineering Laboratory confirm this increased demand (see Table 7). In some cases the required AEA to meet the desired air content more than doubled for cylinders cast with fly ash compared with similar cylinders without fly ash. The increased AEA demand for some batches may also be due to the higher ambient air temperatures associated with these batches. It has been shown that an increase in air temperature of 30 F at the time of mixing can more than double the AEA demand to maintain a particular air content. Unfortunately air temperature and mix temperature were not measured throughout the experimental program.

It has been shown that if fly ash concrete has a low AEA demand, then the addition of AEA will cause a proportionally greater increase in air content. However, if the fly ash concrete has a high AEA demand, then the relationship may be nonlinear. This suggests that if high carbon ashes are used, the quantity of air entraining admixture to add to obtain a particular air content may be not only higher but more unpredictable as well (11, 26).

Carbon content is not the only characteristic of fly ash which influences the AEA demand. The surface area (or fineness) of fly ash can also affect the AEA dosage rate of a mix. The greater the surface area the higher the amount of AEA required to maintain a particular air content (20). There is also evidence that the amount of water soluble alkalies (expressed as Na_2O) present in a mix tend to decrease the amount of AEA required to produce a constant air content (10). But the alkali content may increase the spacing factor (distance between entrained air bubbles) which would reduce the effectiveness of the overall air void system (22). Studies by the Bureau of Reclamation show that as the water-to-cement ratio is reduced the spacing factor decreases for mixes with the same air content. Since fly ash may offer some reduction in mixing water required, it may reduce the spacing factor, which would make the air void system more effective (13).

Obviously more work needs to be done concerning the effect of fly ash on the air void system of concrete.

Although the amount of air initially entrained in fly ash concrete can be controlled by the air entraining dosage rates, recent studies have shown an unusually high rate of air loss in the fresh concrete, especially with prolonged mixing (17, 24).

The School of Civil Engineering at Oklahoma State University completed a study on the freeze-thaw durabilty of Class C fly ash in concrete. They tested concrete prisms for transverse frequency in accordance with ASTM C215-60 and for durability in accordance with the ASTM test for Resistance of Concrete to Rapid Freezing and Thawing (C666-77). Their findings indicate that internal deterioration caused by rapid freezing and thawing is not significantly influenced by cement replaced with fly ash. Cement was replaced on a 1:1 basis and the highest durability ratings were given to the mixes containing 50% fly ash (26). It should be noted that the fly ash used in this study is not the same as that available to Oregon. Additional research is still needed concerning the effect of fly ash (especially Class C) on freeze-thaw durability and the air void system of concrete. However, most researchers agree that fly ash has a relatively insignificant effect upon this entrained air system. Perhaps the best evaluation of the durability of fly ash concrete is reached through physical testing.

430 Resistance to Sulfate Attack

Soluble sulfates which exist in soils and ground waters can lead to deleterious expansion in portland cement concrete. In studies by the Bureau of Reclamation (21), Class F fly ash from bituminous coal has been found to improve the resistance of concrete to sulfate attack. Other work has reinforced this finding (7). The Bureau's data indicates, however, that Class C ashes may not improve sulfate resistance. In some cases their use radically decreases concrete resistance to sulfate attack. Apparently the reduced resistance is due to the lack of Fe_2O_3 in the glass and the high lime content of these ashes (21). However, the effect of Class C fly ash on the expansion of concrete due to sulfate attack has not been fully established. Several research investigations are currently in progress to determine the sulfate resistance of concrete containing Class C fly ash. It should be noted that sulfate attack has not been a significant problem in past OSHD projects.

440 Heat of Hydration

The chemical reactions that occur as portland cement hydrates are exothermic processes. Up to 120 calories, per gram of cement, may be liberated. The heat of hydration is of interest since hydration can result in a large rise in temperature in the interior of a large concrete mass. The exterior dissipates heat more rapidly so that a temperature differential may occur and during subsequent cooling, serious cracking may result (18).

For practical purposes it is not the total heat of hydration that matters but the rate of heat evolution. When fly ash is incorporated into portland cement concrete, the pozzolanic reactions of the alumino-silicates in fly ash with the calcium hydroxide liberated by the C_3S and C_2S components of portland cement, take place more slowly than C_3S reactions and approximate the slower reaction rate of C_2S. This, combined with the dilution of the portland cement component by fly ash, results in a reduced rate of heat evolution and reduced ultimate heat of hydration (24).

Berry and Malhotra (3) report that 30 percent substitution of portland cement with a fly ash reduced the maximum temperature rise in concrete (which occured four days after placement) from 116 F for plain concrete to 91 F for fly ash concrete (16). Several others have confirmed that the addition of fly ash to portland cement concrete results in a lower heat of hydration of the mix (5, 21, 24).

Because mass concrete is seldom incorporated on OSHD projects, thermal cracking is generally not a problem. There are, however, instances (from a heat of hydration standpoint) where the addition of fly ash to concrete would be ideally suited, such as in large bridge piers.

450 Time of Set and Strength Gain Pattern

It has been shown that the addition of fly ash to PCC increases the time of set and causes a reduction in strength, over plain concrete, at early ages (26). This is due to the delay in the reaction between the silica and calcium hydroxide. For a typical low calcium fly ash, Owens and Butler (19) showed that the pozzolanic reaction commenced at 11 days after hydration at 68 F. Similarly, research by Diamond and Lopez-Flores (6) showed that a 30 percent cement replacement with low calcium fly ashes gave no contribution to strength of ASTM C109 mortars at 1, 3, and 7 days. However, thereafter contribution of the pozzolanic reaction was observed and by 90 days strength of the cement-fly ash mortars were equivalent to the reference portland cement (16).

The rate of strength development is higher for the high lime ashes due to the availability of the hydroxyl, sulfate, and calcium ions from the hydration of the fly ash itself (16). Also, the finer the fly ash the greater the pozzolanic activity and the quicker the reaction products will form.

460 Water Requirements

The addition of fly ash to portland cement concrete may alter the water requirements of the mix. Most studies lead to the conclusion that fly ash does not increase the water requirement of the mix and often reduces it (1). However, if high carbon and/or coarse ashes are used the water requirement may increase due to absorption of water by carbon particles and coarse fly ash particles causing interference with the motion of aggregate particles in the fresh mix. The reason for water reduction by the addition of fly ash to the mix is not well understood but it may occur because of adsorption of very fine fly ash particles on portions of the cement particle surfaces. This would cause dispersion of the cement particles, as occurs with organic water-reducing admixtures (12). The water requirement of fly ash concrete is an important characteristic because of its influence on strength through the water cement ratio. Water reduction could be expected from fly ashes available to Oregon because of their high fineness and low carbon content.

500 QUALITY ASSURANCE OF FLY ASH AS AN ADMIXTURE IN PCC

510 The Need for a Quality Assurance Program

To say that fly ash is "produced" is somewhat of a misconception since it is actually the by-product of the production of electrical power. Since the primary objective of power plant officials is the efficient combustion of available coal, changes in boiler operations may cause variability in fly ash properties. A stop-start process, changes in coal source, and unplanned operational events are examples of industry practices which require good communication and cooperation between the fly ash marketer and the plant operator (17).

Due to the possibility of a material with variable properties, the use of fly ash on future OSHD projects would require implementing a quality assurance program, by OSHD, to insure a uniform product. The requirement of uniformity cannot be overemphasized. If the chemical and physical characteristics of fly ash are kept constant, then functional mix designs can be developed which will permit an accurate estimate of concrete properties. However, due to the complex nature of the chemical reactions that occur in the hydration of fly ash concrete, changes in fly ash characteristics cannot be predictably compensated for by respective changes in the mix design.

For example, both fineness and loss on ignition of fly ash will influence air entraining admixture demands. If both of these properties are varying, then an accurate estimate of the necessary admixture dosage to obtain a particular air content is difficult. Variation in the specific gravity of fly ash is another example of how non-uniformity can influence the concrete mix. OSHD uses the absolute volume theory in preparing mix designs. If the volume of fly ash fluctuates for a given weight, then yield and water cement ratio will also vary.

520 Specifications for Fly Ash

521 OSHD Specifications

The Oregon State Highway Division has developed special provisions for the use of fly ash in portland cement concrete for various projects. On the Marion Street Bridge project, for example, Class F fly ash was allowed as a substitute for 15% of the portland cement by weight (on a 1.25:1 basis) for all concrete except the Class 4500-3/4" mix. Fly ash was required to conform to ASTM C618 including Tables 1, 1A, 2, and 2A.

On several projects let in 1983, the contractor was required to develop the concrete mix design. Class C or Class F fly ash was allowed in some structures but not in pavements, bridge decks, or with prestress steel. Fly ash was to conform to C618 except that LOI was reduced to a maximum of 4% and amount retained on No. 325 sieve changed to a maximum of 30%.

522 Specifications Used in Nearby States

The State of Washington is developing specifications for Class F fly ash produced at Centralia. The fly ash must conform to the requirements of ASTM C618 with the optional requirements and a further limitation that the loss on ignition be a maximum of 1.5%. The contractor will also be required to design a mix and meet a 28 day compressive strength criterion.

Fly ash is allowed to replace 15% of the cement on a 1:1 basis in California. They use ASTM C618 but require the loss on ignition to be below 4%. Greater restrictions for loss on ignition are generally the only area where states deviate from ASTM C618.

530 Testing of Fly Ash

The most commonly recognized source for standard specifications and testing for fly ash is ASTM. ASTM first published a standard specification (C350) on fly ash for use as an admixture in concrete in 1954. In 1968, ASTM published C618 which brought both fly ash and natural pozzolan under a common specification. In 1977 they revised C618 to provide for Class C and Class F fly ash. The most recent designation for C618 at the time of this writing is the 1983 revision. This revision deletes the optional chemical requirement of magnesium oxide. Following is a summary of the specifications and tests used by ASTM, as well as a description of the significance of each.

531 Chemical Requirements

531.1 Total oxides

The sum of silicon dioxide, aluminum oxide, and iron oxide shall exceed 70% and 50% by weight for Class F and Class C respectively. This specification was adopted to insure that there are adequate reactive constituents to react with lime in the presence of water and form the cementing properties (11). The lower limit for the Class C ash is a reflection of its normally higher lime content. The 3 fly ashes tested in the experimental program met the requirements for total oxides. Past testing indicates that fly ash sources available to Oregon have consistently been able to meet this specification.

531.2 Sulfur trioxide

ASTM limits the sulfur trioxide content to 5%. This restriction was implemented to avoid a harmful sulfate reaction due to an excess content in the hardened concrete. However, ASTM's specifications may be low. There is evidence that this compound is not as damaging in the final fly ash concrete as has been generally supposed (1). The sulfur trioxide content for the Boardman ash used in the experimental program exceeded the permissible level by 3%. No tests were conducted to determine the effect of the higher content in the hardened concrete. Most agencies still use the 5% limit; however, limits as low as 3% have been reported.

531.3 Moisture content

The purpose of the 3% restriction of moisture on both Class F and Class C ashes is to reduce the difficulties associated with storage and handling of a damp product, and to avoid the sale of significant amounts of water as mineral admixture. In the case of Class C, where the fly ash may form cementing compounds in the presence of water, the restrictions are especially necessary. Many states have adopted a 1% maximum which seems realistic for fly ashes available to Oregon, where moisture contents generally run below 0.1%.

531.4 Loss on ignition

This test involves igniting a moisture free sample of fly ash to a constant weight at a temperature of 1382 +/- 122 F and measuring the loss of weight. As mentioned previously, the loss on ignition is an indicator of the amount of carbon in the fly ash. The amount of carbon has been found to be directly proportional to the amount of air entrainning agent required. At present, ASTM allows a loss on ignition of 12% for Class F and 6% for Class C. Since carbon imparts no favorable qualities to fly ash concrete, keeping it as low as possible is beneficial. The loss on ignition for the 3 fly ashes used in the experimental program were significantly below the ASTM specification.

531.5 Available alkalies

This specification is an optional chemical requirement. It was created for application only when concrete containing reactive aggregates is encountered. The limit for available alkalies is 1.5% for both Class F and Class C.

531.6 Magnesium oxide

There has been concern by OSHD personnel regarding the quantity of magnesium oxide in the fly ash from Boardman, where it has on occasion exceeded the pre-1983 ASTM limit of 5%. Evidently ASTM feels that the possibility of expansion and disruption of concrete due to magnesium oxide in the fly ash can be accurately evaluated by the autoclave expansion test. They feel that magnesium oxide contents higher than 5% are acceptable so long as the autoclave expansion does not exceed 0.8%. In 1983 ASTM dropped its 5% requirement for magnesium oxide.

532 Physical Requirements

532.1 Fineness

Assuming the presence of sufficient silica and aluminum, fineness is the most important characteristic of fly ash that relates to its pozzolanic activity. Research has shown that there is a linear relationship between pozzolanic activity and the amount retained on the No. 325 sieve for materials with 75 - 90% passing the No. 325 sieve (11). ASTM restricts the amount retained on the No. 325 sieve to 34%. Fineness has also been correlated to air entraining admixture demands, but to what degree has not been established.

532.2 Pozzolanic activity index

ASTM provides 2 tests for the evaluation of the pozzolanic activity index. One is an activity index with portland cement and the other with lime. The requirements are compressive strengths of 75% of the control in the case of portland cement and 800 psi for lime. Neither test provides a useful indication of the cementing potential of a pozzolan. The test with portland cement is unpopular, both for the 28 day delay required to run the test, and the criticism concerning the lack of correlation with performance of concrete at normal test ages. If the test is used for source qualification only, the delay period becomes less serious (4).

532.3 Water requirements

Water requirements for flow and workability of mortars and concretes containing fly ash influence the water cement ratio and thus the total paste volume used in the mix (15). Therefore, a high water requirement is undesirable. Also, if the water requirement is changing, this can lead to variability in the concrete properties. ASTM limits the water requirement of fly ash to 105% of a portland cement control mortar, but has no specification for uniformity. The fly ashes used in the experimental program were below the 105% restriction.

532.4 Autoclave expansion or contraction

This test protects against the delayed expansion that could occur if sufficient amounts of MgO are present as periclase, which expands as it hydrates. It involves subjecting a specimen containing 25 parts by weight of fly ash and 100 parts by weight of portland cement to a high pressure saturated steam environment and measuring its expansion. The autoclave requirements of 0.8% expansion were met by the 3 fly ashes tested in the experimental program.

532.5 Drying shrinkage

The increase in drying shrinkage of mortar bars at 28 days is an optional ASTM physical requirement. The test gives the difference in drying shrinkage between a control and a test mix. The initial measurement of the 1 inch mortar prisms is made after 7 days of moist curing and the final measurement following 28 days of air storage. The meaningfulness of the results must be open to question since such small sections will dry rapidly, before any significant pozzolanic reaction has taken place (4). Research has shown that the drying shrinkage of plain concrete and fly ash concrete were essentially the same (11). The fly ash samples from the experimental program easily met the ASTM requirements of .03% shrinkage.

532.6 Uniformity requirements

ASTM provides uniformity requirements for specific gravity, percent retained on the No. 325 sieve, and an optional requirement for air entraining dosage demands. As previously discussed, uniformity of fly ash is an important characteristic. The specifications given in C618 seem realistic, however, no work has been done to evaluate the uniformity of fly ashes available to Oregon on a regular basis.

532.7 Reactivity with cement alkalies

This is an optional test to be applied only when fly ash is to be used with aggregate that is regarded as deleteriously reactive with alkalies in cement. It involves measuring expansion of mortar bars after 14 days of moist curing at 100 F. Comparison is made between a control mixture and a job mixture. The control mixture is composed of portland cement, Pyrex glass, and water while the job mixture contains portland cement, Pyrex glass, fly ash, and water. The portland cement and the fly ash replacement ratio used in the job mixture is the same as that proposed for actual applications. ASTM limits the mortar expansion at 14 days to a maximum of 0.02% for both Class F and Class C ashes. Research has indicated that this requirement appears to be infeasible since even control mortars have expansions far in excess of this limit due to the highly reactive glass (8, 24). A better evaluation would be reached by requiring the job mixture to have an equal or lower expansion than the control after the 14 day period.

540 Testing Costs

To perform all the chemical and physical tests, including the optional tests in ASTM C618, is somewhat costly and time consuming. Table 10 shows the cost and time associated with testing fly ash by the Engineering Laboratory as per 1983 prices. The total cost of the chemical tests are lower than the individual tests because of the interrelationship between tests. For example, in order to determine the MgO content you must first determine the silicon, aluminum, and iron

TABLE 10 - COST AND TIME OF TESTING FLY ASH

Tests Performed by the Chemistry Section

	Test	Cost	Time Required to Perform Tests (calendar days)
1.	$SiO_2 + Al_2O_3 + Fe_2O_3$ content	$144.00	NA
2.	SO_3 content	36.00	NA
3.	MgO and Available Alkalies	36.00	NA
4.	Moisture content and loss on ignition	36.00	NA
5.	Fineness (% retained on the No. 325 sieve)	36.00	NA
	Total costs to perform all tests	$200.00	-
	Total time required to complete testing	-	6 (working days)

Tests Performed by the Physical Testing Section

	Test	Cost	Time Required to Perform Tests (calendar days)
1.	Pozzolanic Activity Index		
	a. With portland cement	$120.00	28
	b. With lime	160.00	7
	Note: The cost of 1a. above includes the test for water requirement.		
2.	Soundness	40.00	2
3.	Increase of drying shrinkage of mortar bars	120.00	35
4.	Air-entrainment of mortar	120.00	2
5.	Reactivity with cement alkalies	396.00	14
	Total costs to perform all tests	$956.00	-
	Total time required to complete testing	-	50

Tests Performed by the Soils Section

	Test	Cost	Time Required to Perform Tests (calendar days)
1.	Specific gravity	$ 15.00	2

oxide contents. The time to complete testing is considerably lower for the chemical tests than the physical. This is due to the extended curing time necessary to complete the physical tests. Also, some of these tests cannot be performed concurrently due to the lack of oven space since they require different curing temperatures. Even though some tests may take fewer days to complete, the actual man-hours spent in running the test may be greater, which explains the higher costs associated with these tests.

600 SUMMARY AND CONCLUSIONS

The investigation of fly ash in concrete was divided into two areas. The first phase consisted of an experimental program while the second phase involved an evaluation of fly ash concrete based on applicable research and reports compiled by other agencies. In the experimental program several batches of concrete with various fly ash sources, replacement ratios, and cement factors were compared. Behavior of the fly ash mixes were referenced to the standard OSHD mixes in the respective cement classes. Comparison between fly ash and non-fly ash mixes was based on compressive strength at 7, 28, and 60 days of moist curing. The evaluation of fly ash concrete centered on those topics which were of interest, but were beyond the scope of the experimental program. Reports from a wide variety of reputable agencies were collected and provided the means to make an accurate appraisal of several fly ash characteristics.

610 Phase I - Experimental Program

Data obtained in this program, as well as results reported elsewhere, provide evidence that both Class F and Class C fly ash can be used to manufacture concrete of comparable strength as that produced from conventional materials. In some cases, fly ash showed higher compressive strengths at both high and low cement factors, depending on the fly ash source and its replacement ratio. The 60 day strengths for concrete containing fly ash were generally higher than the reference at the Class 2000 and Class 5000 mixes but were lower for the Class 3000 mix. However, the FAC strengths were higher than the design strength for the Class 3000 mixture and were compared to only one (unusually high) reference mix. Strengths for the Class C ash from Boardman at a 1:1 replacement ratio were comparable to the same ash at a 1.25:1 replacement for every cement factor.

The experimental program verified the variable properties and characteristics often associated with fly ash and fly ash sources on compressive strengths of concrete cylinders. The data occasionally showed marked differences in strengths for changes in fly ash source or replacement ratio or both.

620 Phase II - Evaluation of Fly Ash Concrete

Several studies involving the effect of fly ash on the properties of portland cement concrete lead to the conclusion that fly ash can be used to improve certain qualities of the hardened concrete. However, consistently superior results in the field depend upon proper quality control, handling techniques, and understanding of the effects of fly ash on portland cement concrete.

Evidence from both the experimental program and published literature conclude that fly ash has no effect on promoting expansion due to the Alkali-Aggregate reaction when used with a high alkali cement. The alkalies in fly ash may be more significant when used with a low alkali cement. Although much is still unclear concerning the effect of fly ash on freeze-thaw durability, some research has indicated that fly ash may actually improve durability depending on fly ash type and replacement level (26). Proper control of air content is perhaps the most important measure in assuring adequate freeze-thaw durability. Other areas where fly ash may influence the properties of concrete include water requirement, workability, heat of hydration, time of set, permeability, and strength gain characteristics.

700 RECOMMENDATIONS

The use of fly ash on a regular basis requires development of specifications, procedures for mix designs and batching, and testing and quality assurance. Future research and development projects should be considered. This section includes recommendations based on the experimental program, previous investigations, and outside reports on the aforementioned areas.

710 Specifications

Adoption of the chemical and physical requirements (Tables 1, 1A, 2, and 2A) of ASTM C-618-83 are recommended with the following changes:

711 Loss on Ignition

Loss on ignition (LOI) be reduced from 12% for Class F and 6% for Class C to 1.5% for both. Keeping the carbon content at a minimum will help control the air content for a particular AEA dosage rate as well as improve the quality of the hardened concrete. A specification for a maximum LOI of 1.5% is a realistic limit since LOI for sources available to Oregon are generally around 0.5%.

712 Moisture Content

Moisture content be reduced from 3% to 1% for both Class F and Class C. This would eliminate any difficulties associated with storage and handling of a damp product as well as the cementing activity that could take place with Class C fly ash. Moisture contents generally run below 0.1% for fly ashes available to Oregon.

713 Fineness

The maximum amount retained on the No. 325 sieve be changed from 34 to 30. This additional restriction will help to ensure adequate pozzolanic activity since pozzolanic activity has been shown to be linearly related to the amount retained on the No. 325 sieve. Ashes available to Oregon normally have about 10% retained on the No. 325.

714 Available Alkalies

The optional chemical requirement (Table 1A) be changed from 1.5% to a maximum of 2% in all cases. However, when available alkalies exceed 1.5% they shall be used in an area where aggregates are nonreactive and/or they shall meet the requirements for mortar expansion discussed in 715 below. Sources of reactive aggregates will be determined by the Materials Section. Increasing the alkali limit to a maximum of 2% will allow for the use of certain ashes available to Oregon, which have at times exceeded the previous limit of 1.5%. They will be permitted after it has been determined that their use causes no deleterious effects. The 2% limit is necessary due to the possible effects of alkalies on the spacing factor of the air void system.

715 Reactivity with Cement Alkalies

The requirement of mortar expansion at 14 days be excluded and a new physical requirement introduced which requires the mortar expansion, for the job mixture, at 14 days to be less than or equal to the control at the same age. The test for mortar expansion shall be run in accordance with ASTM C441-81.

720 Mix Design and Batching Procedures

The standard OSHD concrete mix design procedures shall be employed when designing a mix containing fly ash. Fly ash shall replace between 10 and 20% of the portland cement by weight. For Class F the substitution shall be at a rate of 1.25 pounds of fly ash for each pound of portland cement replaced. For Class C the substitution shall be at a rate of 1.00 to 1.25 pounds of fly ash for each pound of portland cement replaced. Fly ash should not be allowed to replace less than 10% of the cement. Water to cement ratios should be calculated using the total cementitious material (cement + fly ash) when FAC is used. Since fly ash increases the cementitious material above a normal portland cement mixture, limits on water to cement ratio should be modified to take this into account. Mix designs shall be based on trial batches to determine the proper proportion of materials as well as the required AEA dosage rate.

730 Testing and Quality Assurance

The standard methods of sampling and testing fly ash for use as a mineral admixture in portland cement concrete are given in ASTM C311-77. ASTM recommends that check tests be performed on individual samples representing not more than 400 tons of material and that all other physical tests and chemical determinations be made on composite samples representing each 2000 tons. The composite sample for this purpose being prepared by combining equal parts of five consecutive samples, each representing 400 tons. The check tests recommended by ASTM are: 1) Fineness, 2) Moisture content, 3) Specific gravity, 4) Loss on ignition, 5) Soundness, and 6) Lime-pozzolan test. Recommendations in this paper are the same as ASTM's with the exception that the lime-pozzolan activity test be excluded and the air entraining agent uniformity requirement be added and that these check tests be performed on samples representing every 50 tons of fly ash used in a specific construction project. It is further recommended that all of the tests in ASTM C311-77 be performed for source qualification every year. This procedure would allow monitoring those fly ash properties, that would most likely vary on a regular basis, and examining other properties at extended periods of time.

When fly ash is used in PCC, compressive strength testing at 90 days should be requested to properly evaluate the delayed strength gain characteristics of FAC. This is especially necessary when Class F fly ash is used.

740 Proposed Special Provisions for Fly Ash

Fly ash should be allowed in cement treated base and structural concrete in accordance with the following proposed special provisions. Fly ash in subgrade treatments is currently under study in the Materials Lab. Fly ash in portland cement concrete pavement needs further evaluation as suggested in Section 750 of this report.

741 Fly Ash in Cement Treated Base

All projects incorporating cement treated base should allow the substitution of fly ash as follows:

> Subsection 308.11 Composition of Mixture - At the request of the Contractor fly ash may be substituted for portland cement for a minimum of 10 percent to a maximum of 20 percent by weight of portland cement. For Class F the substitution shall be at a rate of 1.25 pounds of fly ash for each pound of portland cement replaced. For Class C the substitution shall be at a rate of 1.00 - 1.25

pounds of fly ash for each pound of portland cement replaced. The Contractor's request shall include a mix design indicating the proportions of aggregate, portland cement, fly ash, and water to be used. For each mix design a single substitution percentage and a single replacement ratio shall be listed for fly ash. A maximum of two requests for mix designs may be submitted without charge. Additional mix designs shall be at the Contractor's expense.

Representative samples (300 pounds of aggregate, 20 pounds of portland cement and 20 pounds of fly ash) of specification materials to be used in the mixture shall be furnished to the Engineer. These samples and the proposed proportions of fly ash shall be received at the Engineering Laboratory Building in Salem at least 21 days prior to producing any of the mixture for use on the project. The laboratory will prepare and test specimens for compliance with the strength requirements and determine the optimum moisture content and relative maximum density of the mixture, based on the contractor's mix design. The Contractor shall not produce CTB mixture for the project until written permission is received fom the Engineer.

The mixture shall be designed to insure that at least 85 percent of the mixture will attain a minimum compressive strength of 750 psi at 7 days. Minimum cement - fly ash content shall be 4 1/2 percent of the dry weight of aggregate.

Subsection 308.16 Fly Ash - Fly ash shall conform to the requirements of Subsection 701.07.

742 Fly Ash in Structural Concrete

Subsection 504.32 of the Standard Specifications should be revised as follows:

Subsection 504.32(xx) Fly Ash - At the request of the Contractor, fly ash may be utilized in concrete in the proportions proposed by the Contractor subject to approval by the Engineer and in compliance with the following:

1. The use of fly ash in bridge decks, portland cement concrete pavements or in concrete incorporating prestressing steel strands will not be permitted.

2. Except for seals, fly ash for use in substructure work, walks, curbs, barriers and other noncritical structures will be considered as a substitute for portland cement for a minimum of 10 percent to a maximum of 20 percent by weight of portland cement. For Class F the substitution shall be at a rate of 1.25 pounds of fly ash for each pound of portland cement replaced. For Class C the substitution shall be at a rate of 1.00 - 1.25 pounds of fly ash for each pound of portland cement replaced.

3. Entrained air in fly ash concrete shall be 4 to 7 percent.

4. Fly ash shall conform to the requirements of Subsection 701.07.

743 Materials - Fly Ash

A new subsection of the Standard Specifications should be added as follows:

Subsection 701.07 Fly Ash

a) Specifications - Fly ash shall be Class C or Class F conforming to ASTM C618 including Tables 1, 1A, 2, and 2A except that: (1) Loss on Ignition (LOI) shall be 1.5% maximum.

(2) Moisture Content shall be 1% maximum.

(3) Amount Retained on the No. 325 Sieve shall be 30% maximum.

(4) Available Alkalies, as Na_2O shall be 2.0% maximum.

(5) In table 2A, Mortar Expansion for the job mixture at 14 days shall be less than or equal to the control at 14 days.

(6) When the available alkalies as Na_2O are greater than 1.5% and less than or equal to 2%, fly ash shall not be allowed in areas of potentially reactive aggregates, as determined by the Engineer of Materials.

b) Prequalification of fly ash - All sources of fly ash shall be prequalified by the Engineer of Materials before use on Oregon projects and once a year thereafter. Fly ash shall conform to the requirements of Subsection 701.07(a) as established herein.

Sampling and testing of fly ash for prequalification shall conform to ASTM C311 except that one 20 pound test sample shall be submitted in a sealed container and shall be a composite sample representing 2000 tons of fly ash production. The sample shall be received at the Engineering Lab at least 8 weeks before its proposed use on the project.

Fly ash that has been prequalified will be accepted for immediate use provided the requirements of certification as set forth in Subsection 106.08 of the Standard Specifications are met.

c) Job Control Sampling and Testing - For each 50 tons of each class of fly ash used on the project, a 10 pound sample will be tested in conformance with ASTM C311 for fineness, moisture content, specific gravity, loss on ignition, soundness, and air entrainment of mortar. A minimum of one sample will be tested for each class of fly ash.

750 Research and Development Projects

751 Investigation of FAC Resistance to Degradation

A testing program to evaluate the abrasion resistance, scaling resistance, and durability of fly ash concrete should be conducted. These properties could be evaluated by performing ASTM C779, C215, C666,and C672, or similar tests.

752 Investigation of the Air Void System of FAC

Some research has shown a higher than usual rate of air loss in fly ash concrete containing certain combinations of cements and fly ash, and accentuated by prolonged mixing (17, 24). Comparison of air contents in the plastic and hardened concretes need to be conducted to assure protection against freeze-thaw degradation.

753 Investigation of Strength Gain Characteristics of FAC

Due to the delayed strength gain characteristics of certain fly ash concretes, work needs to be done to see if reliable curves can be generated to estimate, at early ages, the ultimate strength of FAC. Perhaps this could be accomplished by performing tests similar to ASTM C918-80 "Developing early age compression test values and projecting later age strengths."

754 Investigation of the Pozzolanic Activity Test

The pozzolanic activity test as outlined in ASTM C311 is performed at a water content determined by the mortar flow test. Therefore, the results for pozzolanic activity depend upon the influence of the fly ash on water requirement of the test mortars. Pozzolanic activity may be better characterized by using fixed water contents. There is also evidence that the lime fly ash proportions used in the pozzolanic activity index with lime, are deficient in lime for highly reactive aggregates (12). Work needs to be done to modify these tests for better evaluation and characterization of fly ash in concrete.

755 Investigation of the Alkali-Aggregate Reaction of FAC

The effect of fly ash on the alkali-aggregate reaction when used with low alkali cements is not well understood. Tests to determine acceptable levels of expansion, and fly ash alkali contents need to be determined.

756 Investigation of Base and Subgrade Stabilization

An investigation is currently being conducted by ODOT on mixed in place base stabilization using lime-fly ash combinations. This study involves determination of optimum lime-fly ash percentages to add to specific subgrade materials and aggregate base materials.