CONSTRUCTION MATERIALS MADE WITH COAL COMBUSTION BY-PRODUCTS

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ABSTRACT

A research program at the Center for By-Products Utilization, UW-Milwaukee, is being conducted to develop new low-cost construction materials primarily using coal combustion by products. This paper reports results of research performed to develop concrete mixture proportions information using fly ash and bottom ash in masonry products. The influence of different types, amounts, and sources of ash on compressive strength and bulk density of concrete are given in this paper. The influence of curing temperature as well as using bottom ash as a replacement of natural aggregates is also reported. It is concluded that low-cost construction materials can be reliably developed using coal combustion by-products at a large savings to producers and consumers.

Keywords: Fly Ash, Bottom Ash, Masonry, Concrete, Compressive Strength, Curing Temperature, Density.

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INTRODUCTION

Fly ash and bottom ash are produced as by-products of coal-fired electricity generation. In many countries of the world, fly ash is widely accepted and used as a cementitious component in portland cement concrete. However, cement replacement by fly ash is often limited to 15 to 30 percent. The production of masonry units is one area where there is potential to use large quantities of fly ash and bottom ash. Because coal ashes are by-products of the coal combustion, their properties are influenced by the nature of the coal and the process by which it is burned. It is, therefore, inevitable that their properties vary from source to source. Detailed studies of using different sources of ash are an important part of understanding behavior of masonry products made from coal ashes.

The objective of this research program was to develop mixture proportions information for different types and different sources of ash used in concrete masonry products, containing high fly ash and bottom ash content, high compressive strength, low bulk density, and low water absorption. The influence of curing temperature were also studied.

MATERIALS

ASTM Type I cement was used. The natural coarse aggregate used was 9.5 mm (3/8 in.) nominal maximum size natural gravel, and the fine aggregate was natural sand.

Class C fly ash from two sources and Class F fly ash from two sources were used. Two sources of bottom ash (Class C and Class F bottom ash) were used as a replacement of natural aggregates. The Class C type ashes result from burning of subbituminous coal. Class F type ashes are produced from combustion of bituminous coal. The typical chemical analysis of Class F fly ash shows less than 10% of material reported as CaO while that of Class C fly ash often shows as much as 15 to 35%.

Chemical composition and physical properties of cement, fly ashes and bottom ashes are given in Table 1 and Table 2.

MIXTURE PROPORTIONS & CONDITIONS OF TEST

In this work, mix proportioned were developed based on preliminary investigations conducted at the Center for By-Products Utilization, University of Wisconsin-Milwaukee [1]. Four different conditions of test were considered as a basis for mixture proportioning.

(1) The ratio of aggregate to cementitious material.

(2) Types and sources of fly ash.

(3) Steam curing temperature cycle.

(4) Use of bottom ash as a replacement of natural aggregates.

A total of 52 mixtures were proportioned. In these mixtures, cement content was varied from 60 to 150 %, and fly ash content ranged from 40 to 100 % of total cementitious materials used. Bottom ash content was used from 40 to 60% as a replacement of the natural aggregates. Aggregate to cementitious ratio ranged from 3 to 6, water to cementitious ratio varied from 0.4 to 0.6. The details of the mixtures are shown in Table 3.

Flow was measured to determine consistency of concrete mixtures. All mixtures were proportioned to obtain approximately constant workability, as measured in terms of flow diameter (Table). A high fluidity (about 9 ± 1 in. flow diameter) was maintained in order to facilitate casting of the specimens in molds.

SPECIMEN PREPARATION

Specimens were made by making mixtures, and casting the fresh, mixed material directly into a steel 2 in. (50.8 mm.) cube mold and consolidating the concrete in the mold using a vibration table. After curing for one day in the fog room (temperature 73°F; 22°C), specimens were removed from molds and placed back in the fog room until the time of test.

For steam-cured specimens, after casting and storing in laboratory conditions for two hours, they were placed in a steam-curing cabinet. Two steam-curing systems were used to compare results. Figure 1(a) and 1(b) show the temperature-rise graph during the two steam-curing periods. After 24 hours of elevated temperature curing, specimens were removed from molds and some tested for one day strength. The rest of the specimens were placed in the fog room until the time of test.

TEST METHODS

The 2-inch cubes were tested for compressive strength in accordance with ASTM C109. The compressive strength measurements done at 3, 7, and 28 days. Bulk density of the cubes were determined in accordance with ASTM C140. Three specimens were tested at each test age.

RESULTS AND DISCUSSION

The effect of ratio aggregate to cementitious material and water to cementitious material ratio on compressive strength and bulk density is given in Table 4. All specimens were cured in the fog room until the time of test. Fly ash used in this test was Class C (F- 1) with 32% CaO chemical analysis. The investigation was carried out on three levels of aggregates to cementitious material ratio of 3, 4.5, and 6, and, water to cementitious ratios were 0.4, 0.5, and 0.6, respectively. Cement content was varied from 60 to 0 percent while fly ash content was varied from 40 to 100 percent. All mixtures had similar workability except for the mixture containing 100% fly ash (which had a very high rate of setting). As can been observed from Table 3, the higher aggregate to cementitious material ratio resulted in lower compressive strength, since in order to keep similar workability for all mixtures, the water to cement plus fly ash ratio had to be increased with increase in the aggregate to cementitious material ratio.

The non-cement mixture (100% fly ash) showed a higher compressive strength than the mixture with 20% cement and 80% fly ash at all test ages. The strength difference is larger at 3 days and 7 days. At the 28-day age, the strength was also higher for the 100% fly ash mixture but not by a significant amount. The high CaO content of the fly ash (Table 1), contributes to higher early strength. If no retarder is used, the large amount of Class C fly ash would lead to rapid setting. Figure 2 shows the compressive strength development with curing ages for the mixtures in which aggregates to cementitious material ratio was 6 to 1. As shown in Figure 2, compressive strength for the mixture containing 100% fly ash is lower than the 40 and 60% cement and higher than the 20% cement mixtures. Because its fast setting, the 100% fly ash mixture was difficult to use to mold test specimens and provide adequate vibration for consolidation.

Table 4 also shows that there are no significant differences in the bulk density of specimens. The bulk density was found to vary between 150 to 156 lb./cu.ft. (2403 to 2499 kg/m^3). The bulk density was generally slightly higher for higher aggregate to cementitious material ratio. For the rest of the test program, on aggregate to cementitious material ratio of 4.5 was selected.

Two sources of Class C fly ash (F-1, F-2) and two sources of Class F fly ash (F-3, F-4) were investigated. For the Class C fly ash, fly ash content was varied from 40 to 100 percent; and, for the Class F fly ash, it varied from 20 to 80 percent. The aggregate to cementitious ratio was selected to be 4.5 for all these additional mixtures. All specimens were moist cured until the time of test.

Figure 3 shows the 28-day compressive strength for concretes made using these four fly ashes. The concretes made using the Class C fly ashes have higher compressive strength than those made using the Class F fly ashes for the same fly ash content. The Class F had a higher water requirement, see Table 2 to achieve equivalent workability, resulting in higher water to cementitious material ratios, and consequently lower strengths. From the comparison of the two sources of the Class C fly ash and the two sources of the Class F fly ash, it can be observed that there are no significant differences in the compressive strength at the same fly ash content. The data also show that the equivalent strength can be obtained by using 80% cement plus 20% Class F fly ash with 60% cement plus 40% Class C fly ash, or 60% cement plus 40% Class F fly ash with 40% cement plus 60% Class C fly ash, i.e., higher cement factor is required for the Class F fly ash mixtures than that for the Class C fly ash mixtures. For higher fly ash content mixtures this trend was not always valid.

Figure 4 gives the bulk density for concretes made using these four fly ashes. The bulk density varied from approximately 150 to 155 lb./cu.ft. (2403-2483 kg/m^3) for the Class F fly ash, and 153 to 158 (2451-2547 kg/m^3) for the Class C fly ash. The Class C fly ashes are finer and have a slightly higher specific gravity (Table 2). Therefore, Class C fly ash concrete mixes generally leads to higher early strength.

The influence of steam curing temperature on compressive strength is shown in Table 5. Fly ash used in this test was Class C fly ash (F-l). Fly ash content was 40%, 60%, 80% of the cementitious material.

From the data in Table 5, it is evident that the compressive strength of cube specimens cured at 150°F (65°C) is consistently higher than those cured at 200°F (95°C). From microscopic studies many researchers have concluded that, with lower temperature curing, a relatively more dense and uniform microstructure of the hydrated cement paste (especially the pore size distribution) accounts for the higher strength [2]. This phenomena was previously reported by Verbeck and Helmuth in 1968 [3].

The data in Table 5 also shows that the compressive strength decreased with the increase in fly ash content for both curing environments. This is similar to previous test results, Table 4, for the fog room cured specimens. For steam-cured specimens, Table 5, the 24 h compressive strength achieved was 64 to 72 percent of the 28-day strength. Generally, under normal temperature curing conditions, in order to obtain 60 to 70 percent of 28-day strength, a period of 7 days of fog room curing is required. The steam-curing method, however, is recommended in the masonry production to achieve higher one-day strengths. Steam curing will shorten curing time and increases production cycle. In general, the higher the curing temperature, the higher the strength gain resulting from it. But it is not always true if the initial curing temperature is too high which would result in non-uniform microstructure and lower strength. From these test results, the optimum steam-curing temperature is 150°F, which is also in general agreement with operating temperatures of plants for masonry products.

Two kinds of bottom ashes were studied: one was Class F bottom ash (B-1) which was used as a replacement of coarse aggregate (4.5 mm (3/8 in) pea gravel); and, another was Class C bottom ash (B2) which was used as a partial replacement of fine aggregate (natural sand). The effect of using the Class F bottom ash (B-1) as replacement for pea gravel on compressive strength is given in Table 6, and the effect of using Class C bottom ash (B-2) as replacement of natural sand on compressive strength is given in Table 6. These investigations were carried out on three levels of aggregate to cementitious material ratio: 3 to 1, 4.5 to 1, and 6 to 1. Among the total aggregates, bottom ash content varied from 40 to 60 percent while sand or pea gravel content varied from 60 to 40 percent, respectively. All mixtures were proportioned to have 60% cement and 40% fly ash. When using Class F bottom ash (B-l) as coarse aggregate, the fly ash used was Class C fly ash (F-l), and when using Class C bottom ash (B-2) as fine aggregate, the fly ash used was Class F fly ash (F-3). In the specimens preparation, all mixtures were adjusted to have similar workability.

For the Class C fly ash together with Class F bottom ash (coarse) mixtures, the data in Table 6 show that the higher the aggregate to cementitious material ratio the higher the water to cement plus fly ash ratio, in order to maintain similar workability. This resulted in lower compressive strength. The test data also show that there are no significant differences with respect to the effect of bottom ash content on compressive strength at a constant aggregate to cementitious ratio. However, there was a very slight decrease in compressive strength with increase in the bottom ash content.

For the Class F fly ash together with Class C bottom ash (fine) mixtures, the test data in Table 7 show that the higher the aggregate to cementitious material ratio, the lower the compressive strength, both due to increased water to cementitious material ratio, to maintain similar workability, as well as due to decreased cementing ability of the Class F fly ash. The strength was also reduced with an increase of bottom ash content. As shown in Table 7, the increase of bottom ash content raised the water to cement plus fly ash ratio, which resulted in lower compressive strength. The increased trend of water to cement plus fly ash ratio required to maintain workability was somewhat more marked for high aggregate content mixtures.

In general, average bulk density of the mixtures containing Class F bottom ash (B-1) and

Class C fly ash (F-1) was found to vary between 137 to 150 lb./cu.ft. (2194-2403 kg/m^3), about 5 percent lighter than no bottom ash mixture (Figure 4). The mixtures containing Class C bottom ash (B-2) and Class F fly ash (F-3) had even more lighter weight. Their average bulk density was found to vary from 119 to 140 lb./cu.ft. (1906-2243 kg/m^3), about 10 percent lighter than no bottom ash mixture (Figure 4). The bulk density decreased with the bottom ash content increase, but the decreasing trend was not very specific.

CONCLUSIONS

The results obtained from the present study leads to the following general conclusions:

(1) This study indicated that fly ash could be used as a partial replacement of cement, and bottom ash as lightweight aggregate in manufacturing of masonry products.

(2) The specimens made with Class C fly ash exhibit higher compressive strength than those with Class F fly ash for the same fly ash content. Because of the higher strengths of the Class C fly ash mixes, it is possible to replace higher amounts of cement than those mixes using the Class F fly ash.

(3) Since the Class C fly ash usually was finer and had a slightly higher specific gravity than Class F fly ash, Class C mixes showed a little higher bulk density.

(4) Steam curing can shorten curing time and increase production cycle. Selecting suitable curing temperature is very important. If the curing temperature is too high, it would cause non-uniform microstructure, resulting in lower strength. The optimum steam curing temperature is about 150°F (65°C).

(5) Bottom ash may be used as a partial replacement of natural aggregates. Large size bottom ash can be used as coarse aggregates, and finer bottom ash used as sand. The percentage of bottom ash which can be used in a mixture composition depends upon its quality and required strength of the product.

(6) As a comparison, specimens incorporating bottom ash have lower density than no bottom ash specimens. Average bulk density of specimens containing Class F bottom ash (as coarse aggregate) was found to very between 137 to 150 lb./cu.ft. (2194 to 2403 kg/m^3); and, 119 to 140 lb./cu.ft. (1906 to 2243 kg/m^3) for the mixture containing Class C bottom ash (as fine aggregate), which is about 5% to 10% lighter than no bottom ash specimens.

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REFERENCES

1. Wei, Lihua, "Utilization of Coal Combustion By-Products for Masonry Production", Master Degree Thesis, The University of Wisconsin-Milwaukee, Milwaukee, WI, January, 1992 (also published as EPRI Technical Report TR100707, May 1992).

2. Naik, T.R., "Production of Masonry Blocks for Developing Countries", Presented in the 7th ASCE Structure Congress, San Francisco, CA, May 1989, 10 pages.

3. Golden, D.M., "EPRI Research to Develop Coal Ash Uses in the USA", Proceedings of Shanghai 1991 Ash Utilization Conference, Shanghai, P.R.China, Vol. 1, EPRI Report GS-7388, September 1991, pp. 5-1 to 5-15.

4. Annual Book of ASTM Standards, American Society for Testing and Materials, Volume 04.01, 1991.

5. Annual Book of ASTM Standards, American Society for Testing and Materials, Volume

04.02, 1991.

6. Verbeck and Helmuth in Proc. of 5th International Symposium on Chemistry of Cement, Vol. III, Tokyo, 1968.

TABLE 3: DETAILS OF MIXTURES USED

Mix No.	Design Option	Cement (%)*	Fly Ash (%)*	Aggregate/ Cementitious	Type of Fly Ash	Type of Bottom Ash
1	1	0	100	3/1	F-1	None
2	1	20	80	3/1	F-1	None
3	1	40	60	3/1	F-1	None
4	1	60	40	3/1	F-1	None
5	1	0	100	4.5/1	F-1	None
6	1	20	80	4.5/1	F-1	None
7	1	40	60	4.5/1	F-1	None
8	1	60	40	4.5/1	F-1	None
9	1	0	100	6/1	F-1	None
10	1	20	80	6/1	F-1	None
11	1	40	60	6/1	F-1	None
12	1	60	40	6/1	F-1	None
13	2	0	100	4.5/1	F-1	None
14	2	20	80	4.5/1	F-1	None
15	2	40	60	4.5/1	F-1	None
16	2	60	40	4.5/1	F-1	None
17	2	0	100	4.5/1	F-2	None
18	2	20	80	4.5/1	F-2	None
19	2	40	60	4.5/1	F-2	None
20	2	60	40	4.5/1	F-2	None
21	2	20	80	4.5/1	F-3	None
22	2	40	60	4.5/1	F-3	None
23	2	60	40	4.5/1	F-3	None
24	2	80	20	4.5/1	F-3	None
25	2	20	80	4.5/1	F-4	None
26	2	40	60	4.5/1	F-4	None
27	2	60	40	4.5/1	F-4	None
28	2	80	20	4.5/1	F-4	None
29	3	20	80	4.5/1	F-1	None
30	3	40	60	4.5/1	F-1	None
31	3	60	40	4.5/1	F-1	None
32	3	20	80	4.5/1	F-1	None
33	3	40	60	4.5/1	F-1	None
34	3	60	40	4.5/1	F-1	None
35	4	60	40	3/1	F-1	**B-1, 40%
36	4	60	40	3/1	F-1	**B-1, 50%
37	4	60	40	3/1	F-1	**B-1, 60%
38	4	60	40	4.5/1	F-1	**B-1, 40%
39	4	60	40	4.5/1	F-1	**B-1, 50%
40	4	60	40	4.5/1	F-1	**B-1, 60%

TABLE 3: DETAILS OF MIXTURES USED (Cont.)

Mix No.	Design Option	Cement (%)*	Fly Ash (%)*	Aggregate/ Cementitious	Type of Fly Ash	Type of Bottom Ash
41	4	60	40	6/1	F-1	**B-1, 40%
42	4	60	40	6/1	F-1	**B-1, 50%
43	4	60	40	6/1	F-1	**B-1, 60%
44	4	60	40	3/1	F-3	**B-2, 40%
45	4	60	40	3/1	F-3	**B-2, 50%
46	4	60	40	3/1	F-3	**B-2, 60%
47	4	60	40	4.5/1	F-3	**B-2, 40%
48	4	60	40	4.5/1	F-3	**B-2, 50%
49	4	60	40	4.5/1	F-3	**B-2, 60%
50	4	60	40	6/1	F-3	**B-2, 40%
51	4	60	40	6/1	F-3	**B-2, 50%
52	4	60	40	6/1	F-3	**B-2, 60%

* Percentages of materials by weight of total Cementitious (Cement + Fly Ash).

** Percentages of materials by weight of total Aggregates.

Design Option:

1--Selecting aggregate to cementitious ratio in mix composition.

2--Using different type and different source of fly ash.

3--Selecting steam curing temperature.

4--Using bottom ash as a replacement of natural aggregates.

Table 1- *Results of Chemical analysis of cement (C), fly ash (F-1, 2, 3, and 4) and bottom ash (B-1, 2)*

Material	Composition, %								
	SiO_2	Al_2O_3	CaO	MgO	Fe_2O_3	K_2O	Na_2O	TiO_2	Loss on Ignition, %
C	27.76	5.3	55.24	5.93	2.86	0.78	0.41	0.36	1.25
F-1	32.23	18.37	31.66	5.09	5.80	0.25	4.92	1.96	0.86
F-2	32.91	19.36	28.85	4.93	5.38	0.34	1.95	1.58	0.64
F-3	41.86	25.95	3.51	1.57	12.44	1.91	0.45	1.34	15.74
F-4	48.21	26.26	2.66	1.14	10.61	1.08	2.26	1.21	7.89
B-1	51.16	17.66	6.05	1.43	22.67	1.45	0.64	0.86	1.80
B-2	46.24	17.45	21.56	4.66	7.08	0.35	0.89	1.40	2.08

Table 2- *Physical properties of cement and fly ash*

Material	Properties, %				
	Moisture Content	Fineness, retained on 45μm, 325 wet sieve	Specific Gravity	Water Requirement, % of Control	Pozzolanic Activity Index with Portland Cement, % Ration to Control, at 28 days, psi[a]
C	0.37	11.3	3.10	100	100
F-1	0.08	33.8	2.66	94	102
F-2	0.80	15.0	2.57	92	114
F-3	0.20	54.4	2.46	106	74
F-4	0.39	37.5	2.36	107	89

[a]145 psi = 1 MPa

Table 4- *The effect of aggregates to cementitious ration on compressive strength and bulk density (F-1 class C fly ash)*

Aggregates to Cementitious material ratio[a]	Cementitious Materials		W/(C + F)	Flow Range, %	Compressive Strength, (psi)			
	Cement, %[b]	Fly Ash, %[c]			3-day	7-day	28-day	Bulk Density, lb/ft^3
3.0	60	40	0.4	120	4830	6280	8680	154.2
3.0	40	60	0.4	128	2300	3740	6620	150.4
3.0	20	80	0.4	130	420	460	2410	153.0
3.0	0	100	0.4	fast set	1680	2260	2960	152.8
4.5	60	40	0.5	122	2870	4290	6500	153.3
4.5	40	60	0.5	128	1700	3010	5620	155.8
4.5	20	80	0.5	146	250	300	1670	153.4
4.5	0	100	0.5	fast set	1300	1730	2280	154.1
6.0	60	40	0.6	122	1800	2410	4420	154.5
6.0	40	60	0.6	120	1240	2020	3870	156.0
6.0	20	80	0.6	117	210	260	1350	154.4
6.0	0	100	0.6	fast set	940	1190	1410	153.6

[a] Among aggregates, 50% is fine aggregate (natural sand) and 50% is coarse aggregate 9.5 mm ($^3/_8$ in. nominal maximum size of pea gravel)

[b] Percentages of materials by weight of total cementitious material (cement + fly ash).

[c] ASTM Test Designation C230

TABLE 5—*The influence of curing temperature on compressive strength.*

	Steam Curing Temperature 150°F (65°C)		Steam Curing Temperature 200°F (93.3°C)		Cementitious Materials	
Curing Time[a]	Compressive Strength, psi	Strength Ratio, %	Compressive Strength, psi	Strength Ratio, %	Cement, %[b]	Fly Ash, %[b]
24-hour	3630	66	2760	64	60	40
3-day	4120	75	2990	69	60	40
28-day	5460	100	4320	100	60	40
24-hour	2650	66	1670	70	40	60
3-day	2800	69	1900	80	40	60
28-day	4040	100	2380	100	40	60
24-hour	1570	68	1390	72	20	80
3-day	1680	73	1410	73	20	80
28-day	2310	100	1940	100	20	80

[a]Higher temperature curing for the first 24 h only. Beginning at one day age, all specimens were stored in a fog room, temperature 73 ± 3°F (22.8 ± −16.1°C) until the time of test.
[b]Percentages by mass of total cementitious material (cement + fly ash). Type I cement and F-1 Class C fly ash. 145 psi = 1 MPa, 1 in. = 25.4 mm, 1 ft^3 = 0.02832 m^3, 1 lb = 0.4536 kgf, and 1°F = 1.8°C + 32.

TABLE 6—*The effect of using bottom ash as replacement of course aggregate on compressive strength and bulk density (B-1, Class F bottom ash).*

Aggregate to Cementitious Material Ratio[a]	Aggregates[b] Bottom Ash, %	Aggregates[b] Sand, %	$\frac{W}{C+F}$	Compressive Strength, psi 3-day	7-day	28-day	Bulk Density lb/ft^3
3.0	40	60	0.37	3700	5960	7830	150.0
3.0	50	50	0.37	3590	5620	7750	145.8
3.0	60	40	0.37	3510	5330	7170	143.5
4.5	40	60	0.47	2800	4370	6540	148.7
4.5	50	50	0.47	2790	4370	6500	146.9
4.5	60	40	0.47	2510	4250	6710	145.2
6.0	40	60	0.54	2240	3140	5500	145.5
6.0	50	50	0.54	2070	3260	5420	146.3
6.0	60	40	0.54	2050	2900	4200	137.0

[a]Among cementitious materials, 60% is Type I cement, and 40% is Class C fly ash (F-1).
[b]Percentages of materials by weight of total aggregates (bottom ash + sand).

TABLE 7—*The effect of using bottom ash as replacement of fine aggregates on compressive strength and bulk density (B-2, class C bottom ash).*

Aggregate to Cementitious Material Ratio[a]	Aggregates[b] Bottom Ash, %	Aggregates[b] Pea Gravel, %	$\frac{W}{C+F}$	Compressive Strength, psi 3-day	7-day	28-day	Bulk Density lb/ft^3
3.0	40	60	0.64	1080	1620	2460	140.3
3.0	50	50	0.70	1080	1420	2430	139.8
3.0	60	40	0.76	700	1000	1760	136.0
4.5	40	60	0.97	510	740	1150	140.6
4.5	50	50	1.11	430	580	930	135.7
4.5	60	40	1.30	270	440	680	129.5
6.0	40	60	1.36	210	310	540	137.4
6.0	50	60	1.63	170	250	370	131.3
6.0	60	40	1.96	100	160	180	118.9

[a]Among cementitious materials, 60% is Type I cement, and 40% is Class F fly ash (F-3).
[b]Percentages by weight of total aggregates (bottom ash + pea gravel). 145 psi = 1 MPa, 1 in. = 25.4 mm, 1 ft^3 = 0.02832 m^3, 1 lb = 0.4536 kgf, and 1°F = 1.8°C + 32.

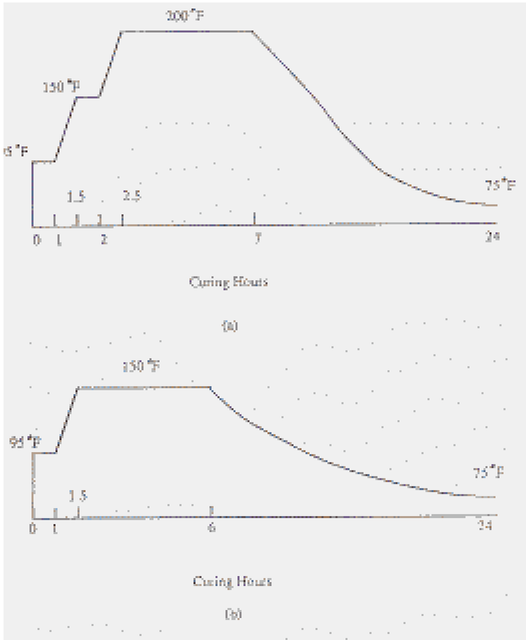

FIG. 1—*Curing temperature change during steam curing period.*

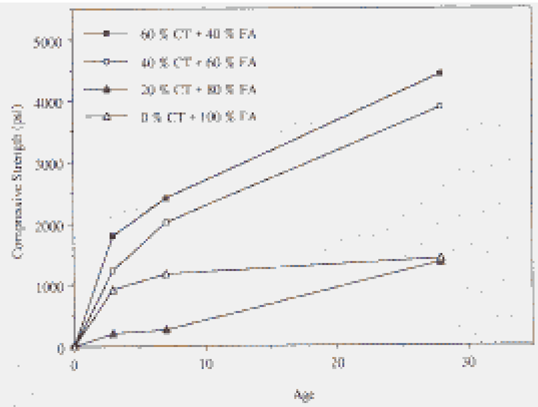

FIG. 2—*Compressive strength versus age for aggregate/cementitious ratio = 6 (CT = cement and FA = fly ash).*

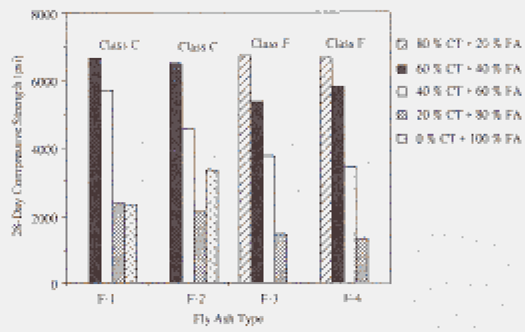

FIG. 3—*Twenty-eight-day compressive strength of concrete made using four fly ashes.*

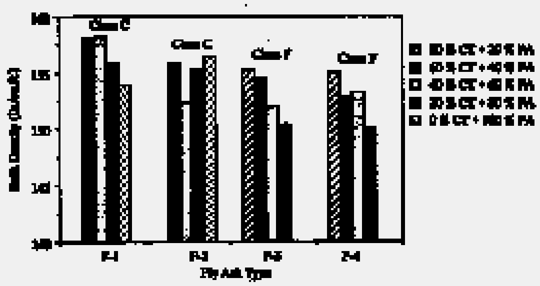

FIG. 4—*Bulk density of concrete made using four fly ashes.*