Pergamon

Cement and Concrete Research, Vol. 28, No. 11, pp. 1555–1569, 1998
Published by Elsevier Science Ltd

0008-8846/98 $–see front matter

PII S0008-8846(98)00132-X

LABORATORY-PRODUCED HIGH-VOLUME FLY ASH BLENDED CEMENTS: PHYSICAL PROPERTIES AND COMPRESSIVE STRENGTH OF MORTARS

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(Received October 8, 1997; in final form August 10, 1998)

ABSTRACT

This paper describes the production of laboratory-produced high-volume fly ash blended cements. The effect of grinding of the Portland cement clinker, fly ash, and gypsum with or without a superplasticizer on the physical properties of the cements, and the compressive strength of the mortars made with the resulting blended cements, is discussed. The use of ground fly ash compared with unground fly ash resulted in a substantial increase in the compressive strength of the mortars; the improvement in the strength seems to increase with an increase in the fineness of the fly ash. This was particularly significant for the coarser fly ash. The superplasticizer interground with the clinker seems to act as a grinding aid in the production of Portland cement. Published by Elsevier Science Ltd

Introduction

Not only is the manufacture of Portland cement highly energy intensive, it also is a significant contributor to the greenhouse gases. The production of every ton of Portland cement contributes about 1 ton of CO_2 into the atmosphere. Minor amounts of NO_x and CH_4 also are released into the atmosphere. The total CO_2 emissions per ton of cement range from about 1.1 ton of CO_2 from the wet process to 0.89 ton from a precalciner kiln. About half of the CO_2 emissions is due to the calcination of limestone (a major raw material), and the other half is due to the combustion of fossil fuels (1). According to Cahn et al. (2), the emissions from the calcination of limestone are fairly constant at about 0.54 ton of CO_2 per ton of cement; the emissions from the combustion depend on the carbon content of the fuels being used and the efficiency of the fuel usage. It is, therefore, imperative that technologies be developed to reduce the production of Portland cement clinker in rotary kilns while maintaining the target production of cement to meet the demands of the construction industry.

In the 1980s, CANMET developed high-volume fly ash (HVFA) concrete, in which 55% to 60% of the Portland cement is replaced by low-calcium fly ash, a by-product of thermal power plants. This type of concrete has demonstrated excellent mechanical properties and durability characteristics, and it is slowly gaining acceptance worldwide (3–9). However, at

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present, fly ash has to be added at the ready-mixed concrete batching plants to produce HVFA concrete; this necessitates additional quality control at the concrete plants, thus raising the cost of the concrete. To overcome this problem, in 1995 CANMET undertook a project to develop a blended cement incorporating high volumes of ASTM Class F fly ash. The blended cement is made by grinding together approximately 55% of low-calcium fly ash, 45% of ASTM Type III Portland cement clinker, and a small amount of gypsum. This blended cement, being factory produced, would eliminate the cost of additional silos at the job site and result in a more uniform concrete.

In a previous study dealing with the effect of grinding on the physical properties of fly ashes and a Portland cement clinker (10), it was found that the specific gravity and fineness of the fly ashes increased with an increase in the grinding time. However, this increase was less significant beyond 2 h. The morphology of the fly ashes was affected by the grinding, as the plerospheres and large irregularly shaped particles were crushed after 2 h of grinding. However, the amount of spherical particles reduced with an increase in the grinding time. There seems to be an optimum grinding time of approximately 4 h for the fly ashes, beyond which the water requirement increased and the pozzolanic activity either decreased or did not increase significantly.

This paper describes the production of laboratory-produced HVFA blended cements. The effect of grinding of the Portland cement clinker, fly ash, and gypsum with or without a superplasticizer on the physical properties of the cements and the compressive strength of the mortars made with the resulting blended cements is discussed.

Scope

Twenty-four blended cements with or without a superplasticizer were produced, incorporating approximately 55% fly ash and 45% Portland cement clinker. For each of the three fly ashes used, six blended cements were produced to have Blaine fineness values of 4,000, 4,500, and 5,000 cm^2/g. In addition, two blended cements were produced for each fly ash, for which the grinding time, instead of Blaine fineness, was kept fixed at 4 h. For comparison, three plain Portland cements with or without superplasticizer also were produced.

The physical properties of the cements were determined, and mortar mixtures were made for compressive-strength determination. Mortar mixtures were made by adding ground or unground fly ash and the laboratory-produced Portland cements to the mixer to compare the compressive strength of these mortars with those made using the blended cements.

Materials

Portland Cement Clinker

A Portland cement clinker for the production of ASTM Type III cement was obtained from a cement producer, and its physical properties and chemical composition are given in Table 1.

TABLE 1
Physical properties and chemical analysis of the materials used.

		Fly ash		
	Clinker†	Lingan	Sundance	Genesee
Physical tests				
Specific gravity	3.23	2.82	2.08	1.95
Fineness				
Passing 45 μm (%)	—	87.4	83.6	63.5
Specific surface, Blaine (cm^2/g)	—	2590	3030	1770
Median particle size (μm)	—	14	12.4	21.2
Water requirement (%)	—	97.9	99.2	95.9
Pozzolanic activity index* (%)				
7 days	—	84.1	94.5	81.7
28 days	—	88.6	106.9	84.5
Chemical analyses (%)				
Silicon dioxide (SiO_2)	22.25	36.85	52.35	62.56
Aluminum oxide (Al_2O_3)	4.51	18.35	23.35	20.85
Ferric oxide (Fe_2O_3)	3.41	35.05	4.65	4.45
Calcium oxide (CaO)	65.54	3.68	13.38	5.83
Magnesium oxide (MgO)	2.85	1.04	1.28	1.45
Sodium oxide (Na_2O)	0.38	0.77	3.60	2.51
Potassium oxide (K_2O)	0.82	1.64	0.58	1.72
Equivalent alkali ($Na_2O + 0.658K_2O$)	0.92	1.85	3.98	3.64
Phosphorous oxide (P_2O_5)	0.22	0.26	0.20	0.12
Titanium oxide (TiO_2)	0.20	0.87	0.75	0.67
Sulfur trioxide (SO_3)	<0.01	1.76	0.21	0.08
Loss on ignition	0.01	2.36	0.32	0.26

* Using ASTM Type I cement.
† Obtained from a cement producer and used for the production of cements in the laboratory.

Fly Ash

Fly ashes from Lingan, Nova Scotia; Sundance, Alberta; and Genesee, Alberta were used in this study. Their physical properties and chemical composition are given in Table 1, and their mineral composition is given in Table 2.

Lingan fly ash, an ASTM Class F ash, contained 3.7% CaO and a high Fe_2O_3 content of 35.1%. The equivalent alkali content ($Na_2O + 0.658K_2O$) of the ash is 1.9%. The ash had a Blaine fineness of 2,590 cm^2/g and a specific gravity of 2.82. The relatively high specific gravity of the fly ash is, to a large extent, related to its high iron content.

Sundance fly ash meets the general requirements of ASTM Class F ash and had a CaO content of 13.4% and an alkali content (Na_2O equivalent) of 4.0%. The Blaine fineness of the ash was 3,030 cm^2/g, and the specific gravity was 2.08.

Genesee fly ash had a relatively low Blaine fineness of 1,770 cm^2/g, and the amount of the ash retained on a 45-μm sieve was 36.5% when wet sieved; thus, this ash fails to meet the

TABLE 2
Mineral composition of the fly ashes.

Type of fly ash	Phases identified				
	Glass	Quartz	Mullite	Magnetite	Hematite
Lingan	x	x	x	x	x
Sundance	x	x	x		
Genesee	x	x			

fineness requirements of ASTM C 618. (ASTM C 618 requires that the amount retained when wet sieved on 45-μm sieve be <34%.) The ash had a relatively low specific gravity, which primarily is related to a large amount of plerospheres (hollow particles filled with smaller spheres) in the sample compared with the fly ashes from Lingan or Sundance. The ash had a CaO content of 5.8% and an alkali content (Na_2O equivalent) of 3.6%. This ash meets the general chemical requirements of ASTM Class F fly ash.

Gypsum

The chemical composition of gypsum is given in Table 3.

TABLE 3
Chemical composition of the gypsum.

	Chemical composition
Free water (T <45°C)	0.03
Combined water (T <230°C)	16.38
Carbon dioxide (CO_2)	4.72
SiO_2 and insoluble matter	2.74
Iron and aluminum oxide ($Fe_2O_3 + Al_2O_3$)	0.85
Lime (CaO)	33.42
Magnesium oxide (MgO)	1.48
Sulfur trioxide (SO_3)	41.0
Chloride	0.011
$CaSO_4{\cdot}2H_2O$	78.27
$CaSO_4$	7.83
SiO_2 + insoluble matter	2.74
Iron and aluminum oxide	0.85
Calcium carbonate ($CaCO_3$)	8.39
Magnesium carbonate ($MgCO_3$)	3.09
Chloride	0.011

Superplasticizer

A superplasticizer of sulfonated, naphthalene formaldehyde condensate in a dry powder form was used in some blended cements.

Grinding Mill

A ceramic grinding mill, 420 mm in length and 500 mm in diameter, was used for grinding the fly ashes and the clinker, and for producing the blended products. According to past experience, this mill works well when approximately 45% of its volume is occupied by the material to be ground and the grinding media charge. The grinding efficiency of the mill is dependent primarily on the amount of the materials to be ground, the ratio of the material to the grinding media, and the size of the grinding media. For this study, a combination of 35 kg of porcelain large cylinders (30-mm thickness and 30-mm diameter) and 35 kg of porcelain medium cylinders (20-mm thickness and 20-mm diameter) was selected for the study on the grinding of cement clinker and fly ashes.

Production of HVFA Blended Cements and Determination of Their Physical Properties

Based on the results of Bouzoubaâ et al. (10), HVFA blended cements in small batches were produced at CANMET using the three fly ashes. The clinker, fly ash, and gypsum were interground in the proportion 43.7:55:1.3, respectively. For each fly ash, blended cements were made with and without the incorporation of dry superplasticizer during the grinding process. The proportion of the superplasticizer was 0.9% by weight of the clinker, fly ash, and gypsum. All the materials were ground together from the beginning. Before grinding, the clinker and the gypsum were crushed and sieved so that all the particles were $<$0.6 mm.

Eighteen blended cements were produced with controlled Blaine fineness values of 4,000, 4,500, and 5,000 cm^2/g, and six others were produced with a controlled grinding time of 4 h. The blended cements produced are designated as follows:

- Blended cement, Lingan fly ash, without superplasticizer = BCLx
- Blended cement, Lingan fly ash, with superplasticizer = BCLSx
- Blended cement, Sundance fly ash, without superplasticizer = BCSx
- Blended cement, Sundance fly ash, with superplasticizer = BCSSx
- Blended cement, Genesee fly ash, without superplasticizer = BCGx
- Blended cement, Genesee fly ash, with superplasticizer = BCGSx

x = 1 for cements with Blaine fineness of 4,000 cm^2/g
x = 2 for cements with Blaine fineness of 4,500 cm^2/g
x = 3 for cements with Blaine fineness of 5,000 cm^2/g
x = 4 for cements ground for 4 h

For comparative studies, three normal Portland cements (clinker + gypsum) with or without superplasticizer were produced. These cements are designated as follows:

- Laboratory-produced Portland cement without the superplasticizer, ground to a Blaine fineness of 4,500 cm^2/g, grinding time 315 min = LPC2
- Laboratory-produced Portland cement without the superplasticizer, ground to a Blaine fineness of ~4,000 cm^2/g, grinding time 4 h = LPC4
- Laboratory-produced Portland cement with the superplasticizer, ground to a Blaine fineness of 4,500 cm^2/g, grinding time 4 h = LPCS2

The percentage of the superplasticizer in LPCS2 was 0.9% by weight of clinker and gypsum.

The specific gravity, specific surface (Blaine fineness), particle size distribution of the cements, and compressive strength of the mortars made with these cements were determined.

The specific gravity of the cements was determined with a Beckman 930 air comparison pycnometer. Past experience indicates that the specific gravity determined according to ASTM C 188 and by the air comparison pycnometer was comparable.

The specific surface of the cements was determined by an air permeability apparatus according to ASTM C 204. The particle-size distribution of the cements was determined by the Microtrac X100 particle size analyzer using scattered light from laser beams projected through a stream of particles suspended in isopropanol. The amount and direction of the light scattered by the particles were measured using an optical detector and analyzed by a computer.

The compressive strength of the mortars was determined according to ASTM C 109 test; however, the flow of the mortar ranged from 72 to 117 and, thus, was outside the limits specified by the ASTM.

Results and Discussion

Specific Gravity

At least two different samples were used for determining the specific gravity of the blended cements. According to ASTM C 188, two conducted tests on the same type of Portland cement should not differ by more than 0.03. For the blended cements investigated in the present study, the variation between two measures conducted on the same material was much higher than for Portland cement and was within 0.1. This high variation is due to the use of a blended product. The specific gravity of the blended cements did not change significantly with grinding time after 2 h (Table 4). This is in line with the results for grinding of fly ashes as reported elsewhere (10). However, it is important to use the specific gravity at a given time of grinding for calculation of the Blaine fineness at that same time, because small differences in the specific gravity make big differences in the calculated Blaine fineness.

Fineness

The effect of grinding time on the Blaine fineness of the clinker, fly ash, and cements with or without the superplasticizer is shown in Figures 1–4. The time required for grinding to obtain the cements with Blaine finenesses of 4,000, 4,500, or 5,000 cm^2/g is given in Table 5. For the Portland cements with or without superplasticizer, the Blaine fineness value did not increase appreciably beyond 5 h of grinding. Grinding the superplasticizer with the clinker and gypsum reduced the grinding time required to obtain the same Blaine fineness as that of

TABLE 4
Effect of grinding on the specific gravity of the blended cements.

	Specific gravity					
	Blended cement with Lingan fly ash		Blended cement with Sundance fly ash		Blended cement with Genesee fly ash	
	Without SP	With SP	Without SP	With SP	Without SP	With SP
After 2 h grinding	3.06	3.09	2.92	2.86	2.79	2.86
After 4 h grinding	3.06	3.08	2.85	2.93	2.73	2.92
After 6 h grinding	3.13	3.19	2.91	2.91	2.70	2.88
After 8 h grinding	3.13	3.23	2.92	2.94	2.90	2.91
After 10 h grinding	3.17	—	2.92	—	2.84	—

SP: superplasticizer.

the Portland cement without the superplasticizer. Despite the reduction in grinding time, the particle-size distribution curves of the cements with or without the superplasticizer were similar (Fig. 5).

For the blended cements, although a reduction in the grinding time was observed when the superplasticizer was interground with the other materials, this resulted in different median particle sizes (Table 5) and different particle size distributions when compared with the blended cements without superplasticizer.

The grinding time required for producing blended cements to specific Blaine finenesses was lower as compared to the time required for producing the Portland cements (Table 5). This is probably due to the introduction of a large proportion of fly ash in the grinding

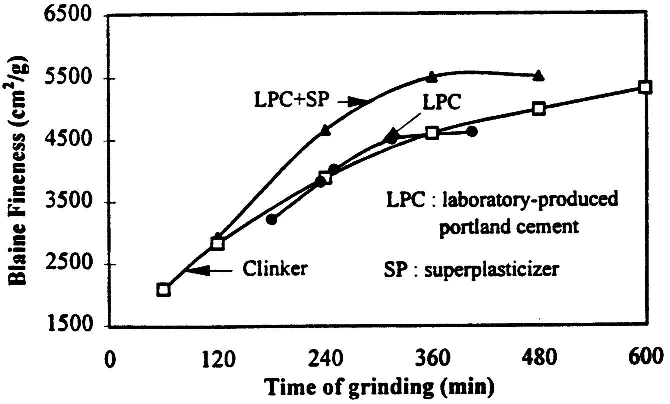

FIG. 1.
Effect of grinding on the Blaine fineness of the clinker and Portland cements with or without superplasticizer.

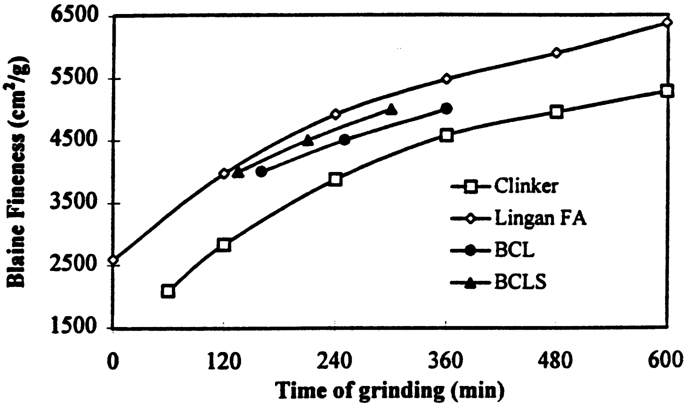

FIG. 2.
Effect of grinding on the Blaine fineness of the clinker, Lingan fly ash, and HVFA blended cements (with the same ash) with or without superplasticizer.

process. However, the blended cements seem to be coarser than the corresponding Portland cement according to the particle size distribution curves shown in Figure 6. In the low particle size range (< approximately 5 μm), the blended cements are coarser than the Portland cement, whereas for particle size > approximately 5 μm, the reverse is true. As the finer particles contribute more to the specific surface than the coarser particles, this suggests that, globally, the blended cements were somewhat coarser than the laboratory-produced Portland cements even though they had the same Blaine fineness.

The Blaine fineness testing method, ASTM C 204, covers determination of the fineness of hydraulic cements. Although the test method may be (and has been) used for determination

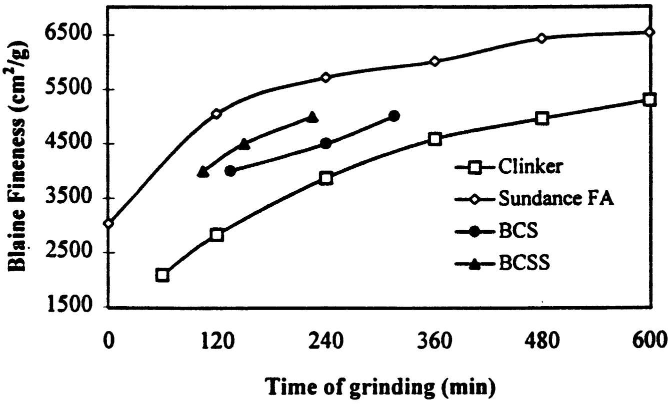

FIG. 3.
Effect of grinding on the Blaine fineness of the clinker, Sundance fly ash, and HVFA blended cements (with the same ash) with or without superplasticizer.

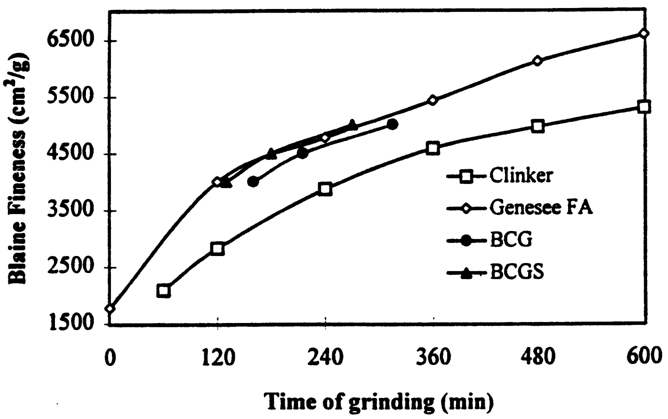

FIG. 4.
Effect of grinding on the Blaine fineness of the clinker, Genesee fly ash, and HVFA blended cements (with the same ash) with or without superplasticizer.

of the fineness of various other materials, it is understood that, in general, relative rather than absolute fineness values are obtained. These results confirm that the Blaine fineness is not a reliable parameter of fineness when fly ash is incorporated in the cements. It also indicated that the time saved for grinding of the blended cements to obtain the same Blaine fineness as the Portland cements was at the expense of the fineness of the final product (Table 5).

TABLE 5
Grinding time required and median particle size of the laboratory-produced cements.

Cement type	Blaine fineness (cm^2/g)	Time required for grinding (min)		Median particle size (μm)	
		Without SP	With SP	Without SP	With SP
Laboratory-produced Portland cement	4000	250	180	7.8	7.8
	4500	315	240	6.8	6.9
	5000	—	330	—	5.7
Blended cement with Lingan fly ash	4000	160	135	7.2	7.3
	4500	250	210	5.6	6.3
	5000	360	300	4.5	5.2
Blended cement with Sundance fly ash	4000	135	105	6.3	7.1
	4500	240	150	5.5	6.4
	5000	315	225	4.8	5.1
Blended cement with Genesee fly ash	4000	160	130	7.5	8.9
	4500	215	180	6.7	7.6
	5000	315	270	5.8	5.7

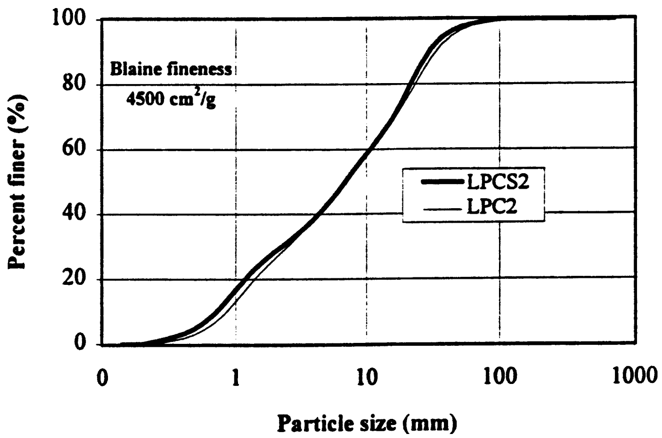

FIG. 5.
Particle size distribution curves for the laboratory-produced Portland cements with or without superplasticizer (Blaine fineness = 4,500 cm^2/g).

Compressive Strength of Mortars

Cement Fineness Controlled by the Blaine Fineness Test. The compressive strengths of the mortars made with the cements ground to a Blaine fineness of 4,500 cm^2/g were determined at 1, 7, 28, and 91 days, and the results are given in Table 6. The water-to-cementitious material (w/c) ratio of the mortars was adjusted to control the flow of the mortars between 105% and 115%; therefore, the w/c ratio of the mortars made with laboratory-produced

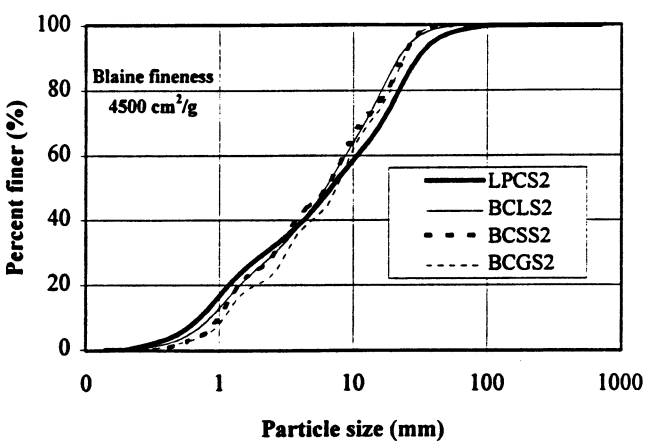

FIG. 6.
Particle size distribution curves for the laboratory-produced Portland cement and the HVFA blended cements (Blaine fineness = 4,500 cm^2/g).

TABLE 6
Effect of grinding mode on compressive strength of the mortars made with blended cements ground to a Blaine fineness of 4,500 cm^2/g.

Mix no.	Cementitious materials type	Fly ash type	Time required for grinding (min)		SP added in grinding mill (%)	SP added in mortar mixer (%)	W/C	Compressive strength (MPa)			
			Cement	Fly ash				1 day	7 days	28 days	91 days
1	LPC2	—	315	—	0	0.7	0.41	24.3	41.2	49.9	—
2	LPCS2	—	240	—	0.9	0	0.41	22.2	43.5	51.5	—
3	BCL2	Lingan	250	—	0	0.7	0.37	13.6	28.8	47.1	64.5
4	BCS2	Sundance	240	—	0	0.4	0.33	11.9	38.6	65.9	79.8
5	BCG2	Genesee	215	—	0	0.4	0.35	11.6	33.5	59.5	75.6
6	BCLS2	Lingan	210	—	0.9	0	0.37	9.9	25.6	42.9	59.7
7	BCSS2	Sundance	150	—	0.9	0	0.33	5.0	31.7	58.7	74.8
8	BCGS2	Genesee	180	—	0.9	0	0.35	5.7	28.5	52.3	68.6
9	LPCS2 + fly	Lingan	240	210	0.9	0.3	0.37	10.5	26.4	46.2	62.4
10	ash ground to	Sundance	240	150	0.9	0	0.33	11.8	34.9	62.8	72.3
11	4.500 cm^2/g	Genesee	240	225	0.9	0	0.35	10.2	34.0	56.4	69.9

Portland cements was 0.41, and that of the blended cements incorporating Lingan, Sundance, and Genesee fly ashes was 0.37, 0.33, and 0.35, respectively.

Portland Cements. The test cubes cast from the mortar mixtures made from LPC2 and LPCS2 had similar compressive strengths at 1, 7, and 28 days, even though the production of the former cement required 75 more min of grinding than that of the latter cement. This, combined with the fineness data, indicates that the superplasticizer added in the grinding mill might have acted as a grinding aid.

Blended Cements with or without Superplasticizer. For a given flow, the dosage of superplasticizer of the mortars made with the blended cements incorporating superplasticizer (Mixtures 6, 7, and 8) was higher than that of the mortars made with the blended cements ground without superplasticizer (Mixtures 3, 4, and 5). The compressive strength of the mortars made with the blended cements incorporating superplasticizer was lower by about 5 to 7 MPa at 28 days than that of the mortars made with the blended cement without superplasticizer. As the blended cements with superplasticizer required less grinding time to reach the same Blaine fineness as the ones without superplasticizer, the lower strengths of the former indicate that the clinker particles in the blended cements with superplasticizer may be coarser than that in the cements without superplasticizer, resulting in less reactivity. This is in line with the results on the particle size distribution of the materials discussed previously.

From these results, it seems that the incorporation of superplasticizer in the blended cements is not effective. However, it is difficult to quantify this due to the different fineness of the blended cements with or without superplasticizer.

TABLE 7
Effect of grinding mode on the compressive strength of the mortars made with blended cements after 4 h of grinding.

Mix no.	Cementitious materials type	Fly ash type	Blaine fineness (cm^2/g) Cement	Fly ash	SP added in grinding mill (%)	SP added in mortar mixer (%)	Flow (%)	Compressive strength (MPa) 1 day	7 days	28 days
12	LPC4	—	~4,000	—	0	2	72	30.9	44.5	53.2
13	LPCS2	—	4,500	—	0.9	2	78	33.7	47.7	62.0
14	45% LPC4 +	Lingan	~4,000	2590	0	0.8	82	8.9	22.6	34.1
15	55% unground	Sundance		3030	0	0.2	84	10.1	25.4	42.7
16	fly ash	Genesee		1770	0	0.6	85	7.9	20.5	31.7
17	45% LPC4 +	Lingan		4920	0	0.6	80	13.0	27.6	42.0
18	55% fly ash	Sundance		5720	0	0.2	80	12.8	36.3	58.6
19	ground for 4 h	Genesee		4770	0	0.4	95	11.5	33.8	51.2
20	BCL4	Lingan	4,570	—	0	1	90	16.7	30.9	49.8
21	BCS4	Sundance	4,640	—	0	0.4	91	12.7	35.9	59.2
22	BCG4	Genesee	4,720	—	0	0.6	92	16.2	38.3	61.1
23	BCLS4	Lingan	4,760	—	0.9	0	90	17.8	30.8	51.7
24	BCSS4	Sundance	5,260	—	0.9	0	117	17.5	50.3	76.8
25	BCGS4	Genesee	5,050	—	0.9	0	108	14.1	44.2	68.3

Effect of Grinding Clinker and Fly Ash Together versus Separate Grinding of the Materials. The compressive strengths of the mortars made with the blended cements BCLS2, BCSS2, and BCGS2 (Mixtures 6, 7, and 8) generally were lower than those made with 45% of the Portland cement LPCS and 55% fly ash ground to a Blaine fineness of 4,500 cm^2/g (Mixtures 9, 10, and 11) (Table 6). This also may be attributed, at least in part, to the lower fineness value of the clinkers in the blended cements.

Cement Fineness Controlled by the Grinding Time. These results have shown that the incorporation of fly ash and superplasticizer reduced the grinding time for the production of the blended cement to a specific Blaine fineness. However, this reduction in grinding time was accompanied by a reduction in the performance of the blended cements, probably due to insufficient grinding of the clinker. To resolve this issue, cements were produced by grinding the materials for a specific time of 4 h based on the results obtained in a previous investigation (10). This also will permit quantification of the effect of the superplasticizer and the mode of grinding of the clinker and fly ashes (ground separately or together with the clinker) on the compressive strength of mortars.

Mortars were made with the Portland cements and blended cements ground for 4 h. Mortars also were made by adding the Portland cement and the fly ashes, ground and unground, to the mixer. The w/c ratio of the mortars was kept constant at 0.33. The flow of the mortars was adjusted by the superplasticizer and ranged from 72% to 117%. Table 7 presents the compressive strength at 1, 7, and 28 days of the mortars.

Portland Cements. For the Portland cements (Mixtures 12 and 13), grinding of the superplasticizer together with the clinker, instead of adding it in the mixer, increased the compressive strength of the mortars by 9%, 7%, and 17% at 1, 7, and 28 days, respectively. However, the mortar made with the LPCS2 required almost 1% more superplasticizer to obtain a flow similar to that with LPC4, in which all the superplasticizer was added in the mixer. This may be attributed to the higher fineness value of the LPCS2. This confirms that the superplasticizer might have acted as a grinding aid when it was interground with the Portland cement clinker and gypsum.

Ground versus Unground Fly Ashes. The mortars made with the LPC4 and 55% fly ash, which had been ground for 4 h (Mixtures 17, 18, and 19), had higher compressive strengths than those made with unground fly ash (Mixtures 14, 15, and 16) due to the finer particle size of the ground fly ashes. The extent of the improvement in the compressive strength by grinding the fly ashes seems to increase with an increase in the fineness of the fly ash and was particularly significant for the coarser Genesee fly ash. For example, the increase in the Blaine fineness of the Lingan, Sundance, and Genesee fly ashes after 4 h of grinding was 2,330, 2,690, and 3,000 cm^2/g, respectively; correspondingly, the 28-day compressive strength of the mortars containing these fly ashes increased by 23%, 37%, and 62%, respectively.

Effect of Grinding Clinker and Fly Ash Together versus Separate Grinding of the Materials. The compressive strength of the mortars made with the blended cements incorporating Lingan or Genesee fly ash (Mixtures 20 and 22) was noticeably higher than that of the mortars made by mixing Portland cement and ground fly ashes of the same origin (Mixtures 17 and 19). For Sundance fly ash, the blended cement gave only slightly better results. This indicates that, in general, the intergrinding of the clinker and fly ashes may yield superior strength results than the separate grinding of the clinker and fly ashes. The higher strength of the mortars made with the blended cements, as compared with that obtained with the mortars when ingredients were batched separately, may be due to the greater homogeneity of the blended products. This is in line with the results reported elsewhere (11).

Blended Cements with or without Superplasticizer. Comparing the compressive strength of the mortars made with the blended cements BCL4, BCS4, and BCG4 (Mixtures 20, 21, and 22) with those made with BCLS4, BCSS4, and BCGS4 (Mixtures 23, 24, and 25), it seems that intergrinding the superplasticizer with the clinker, fly ash, and gypsum resulted in increased compressive strength of the mortars. This probably is due to the greater fineness of the cement incorporating superplasticizer. However, it should be noted that the flow of these six mortar mixtures varied from 90% to 117%, which might have affected the strength results.

Mortars with Genesee Fly Ash. Figure 7 summarizes the effect of grinding on the compressive strength of the mortars incorporating Genesee fly ash. Grinding of the fly ash improved the compressive strength of the mortars substantially. The combined grinding of the clinker, fly ash, gypsum, and superplasticizer seems to generate the highest compressive strength for this combination of materials. These results show that a fly ash not meeting the fineness requirements of ASTM standards can be used for producing a blended cement with excellent strength development.

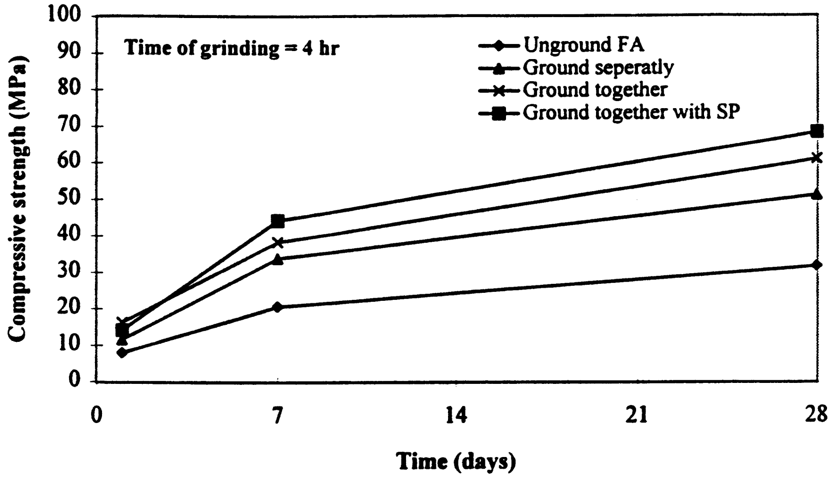

FIG. 7.
Comparison of the different modes of grinding on the compressive strength of the mortars with Genesee fly ash.

Practical Limitations on the Use of HVFA Blended Cements

The authors do not envision major problems in the use of HVFA blended cements for use by the ready-mixed concrete industry. Notwithstanding the above, the ready-mixed concrete would need to provide additional silo capacity, and concrete engineers would have to ensure that additional curing is provided to be sure of strength gain of concrete at early ages.

Summary and Conclusions

Based on the test results obtained in this investigation, the following conclusions can be drawn.

1. For the laboratory-produced Portland cements with or without superplasticizer, the Blaine fineness did not increase appreciably beyond 5 h of grinding. When the superplasticizer was interground together with the clinker and gypsum, the grinding time required to obtain the same specific surface as that without the superplasticizer was reduced.
2. For the blended cements, when the fly ashes were ground together with the clinker and gypsum, the time required to obtain the same Blaine fineness as the laboratory-produced Portland cement was reduced. An additional reduction in grinding time was observed when the superplasticizer was interground with the clinker, gypsum, and fly ashes.
3. The use of ground fly ash compared with the use of unground fly ash resulted in a substantial increase in the compressive strength of the mortars. The improvement in the strength seems to increase with an increase in the fineness of the fly ash and was particularly significant for the coarser fly ash.

4. A blended cement having excellent strength development can be produced with a coarse fly ash not meeting the ASTM standards for fineness.
5. The superplasticizer interground with the clinker seems to act as a grinding aid in the production of Portland cement. However, the effect of intergrinding the superplasticizer with the clinker and fly ash on the properties of the resulting blended cements is still not clear and additional investigation is needed.

Acknowledgments

This investigation was jointly funded by Environment Canada and CANMET, Natural Resources Canada with funds originating from PERD (the Federal Interdepartmental Program of Energy Research and Development). Grateful acknowledgement is made to Mr. Donald Rose, Project Engineer, Environment Canada, for his helpful comments during the investigation.

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