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Reduction in water demand of non-air-entrained concrete incorporating large volumes of fly ash

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Abstract

This paper presents the results of an investigation dealing with the reduction in water demand of the non-air-entrained concrete incorporating large volumes of ASTM Class F and C fly ashes. The eight fly ashes investigated were from Canada and the USA, and the percentage replacement of fly ash in concrete was 55% by mass of Portland cement. No superplasticizer was used in the concrete mixtures. The test results show that the reduction in water demand of the concrete incorporating the fly ashes ranged from a low of 8.8 for Lingan fly ash from Nova Scotia, Canada to a high of 19.4% for Coal Creek fly ash from the USA. The 1-day compressive strength of the concrete ranged from 6.3 MPa for fly ash from Belews Creek, USA to a high of 13.9 MPa for fly ash from Thunder Bay, Canada. The 28-day compressive strength of the concrete ranged from 30.7 to 55.8 MPa. © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: Compressive strength; Concrete; Fly ash; Water demand; Water-reducing ratio

1. Introduction

The International Centre for Sustainable Development of Cement and Concrete (ICON), CANMET has an ongoing research project dealing with the use of large volumes of fly ash in concrete. The concrete so developed has become known as high-volume fly ash (HVFA) concrete [1]. The air-entrained HVFA concrete has a low water-to-cementitious ratio of about 0.30, and the replacement of cement by fly ash is about 55% by mass basis. The high slumps are achieved by using large dosages of superplasticizers. However, in developing countries, the superplasticizers are relatively expensive. Fly ash utilization could be increased in developing countries if less costly superplasticzers were developed or if mixtures proportions were refined to preclude the need for superplasticizers. The purpose of this research was to study the latter of these two alternatives.

2. Scope

A total of nine concrete mixtures, eight incorporating fly ash and one control, were made. The ratio of fly ash to (fly ash + cement) was 55%[1] by mass. The water-to-cementitious materials ratio ranged from 0.34 to 0.39 for fly ash concrete mixtures, and was 0.43 for the control mixture. The properties of the fresh concrete were determined, and test cylinders were cast for compressive strength testing at various ages.

3. Materials

3.1. Portland cement

ASTM Type I normal Portland cement was used. Its physical properties and chemical composition are shown in Tables 1 and 2, respectively.

3.2. Fly ash

Fly ashes from eight different sources in Canada and the USA were used. Their physical properties and chemical composition are also shown in Tables 1 and 2, respectively.

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[1] This percentage was arrived at as a result of the various optimization studies performed at CANMET.

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Table 1
Physical properties of the cement and fly ashes

		Fly ash							
	ASTM type I cement	Point Tupper	Lingan	Sundance	Forestburg	Thunder Bay	Belledune	Belews Creek	Coal Creek
Specific gravity	3.09	2.58	2.82	2.08	1.97	2.43	2.61	2.32	2.55
Finess									
Retained 45 μm (%)	6.9	24.8	12.6	16.4	21.4	10.3	–	20.2	23.9
-specific surface, Blaine (cm^2/g)	4020	2260	2730	3060	2310	2400	1874	2300	2200
-median particle size (μm)	–	14.0	14.0	12.4	17.8	13.2	–	–	–
Water requirement (%)	–	96.5	97.9	94.0	93.5	93.0	–	93.7	92.7
Strength activity index (%)									
7 days	–	79.6	84.1	94.5	82.4	85.1	–	84.7	87.3
28 days	–	89.2	88.6	106.9	91.0	104.3	–	95.8	92.7
Compressive strength (MPa)									
7 days	33.0	–	–	–	–	–	–	–	–
28 days	40.8	–	–	–	–	–	–	–	–

All tests were performed according to ASTM C 618 and C 311 [2,3].

3.3. Aggregates

Crushed limestone with a maximum nominal size of 19.0 mm was used as the coarse aggregate. The fine aggregate was natural sand from Ottawa region. The coarse and fine aggregates were separated into different size fractions and recombined to a specified grading as shown in Table 3. The coarse and fine aggregates have the same specific gravity of 2.70, and water absorption of 0.60% and 0.80%, respectively.

3.4. Chemical admixtures

No air-entrained admixture or superplasticizer was used in the concrete mixtures.

3.5. Mixtures proportions

The concrete mixtures proportions are given in Table 4. The mixtures were proportioned to have a slump of 60 ± 10 mm to develop data on low slump concrete. The fly ash to (fly ash + cement) ratio was kept constant at 55%. The water-to-cement ratio of the control mixtures was selected to be 0.43 with a cement content of 396 kg/m^3 of concrete. For the HVFA mixtures, the cementitious materials content was kept constant at 396 ± 5 kg/m^3 but the water content was decreased in order to maintain a slump of 60 ± 10 mm.

3.6. Properties of fresh concrete

The concrete was mixed in a laboratory counter-current mixer for a total of 5 min. The properties of the fresh

Table 2
Chemical composition of the cement and fly ashes

		Fly ash							
%	ASTM type I cement	Point Tupper	Lingan	Sundance	Forestburg	Thunder Bay	Belledune	Belews Creek	Coal Creek
Silicon dioxide (SiO_2)	20.96	42.74	36.85	52.35	56.75	41.99	53.94	56.20	50.50
Aluminum oxide (Al_2O_3)	4.58	20.29	18.35	23.35	21.51	21.44	16.61	30.05	15.36
Ferric oxide (Fe_2O_3)	3.28	23.71	35.05	4.65	4.89	4.55	20.53	5.06	8.76
$SiO_2 + Al_2O_3 + Fe_2O_3$	–	86.74	90.25	80.35	83.15	67.98	96.08	91.31	74.62
Calcium oxide (CaO)	64.14	4.17	3.68	13.38	8.83	15.81	0.31	1.06	15.60
Magnesium oxide (MgO)	2.68	1.22	1.04	1.28	1.58	3.18	1.14	0.81	3.96
Sodium oxide (Na_2O)	0.28	0.88	0.77	3.60	3.89	7.03	0.42	0.31	2.49
Potassium oxide (K_2O)	0.94	2.56	1.64	0.58	1.14	0.36	1.94	2.24	1.96
Equivalent alkali ($Na_2O + 0.658K_2O$)	0.90	2.56	1.85	3.98	4.64	7.27	1.70	1.78	3.78
Phosphorous oxide (P_2O_5)	0.22	0.68	0.26	0.20	0.36	0.58	0.78	0.24	0.14
Titanium oxide (TiO_2)	0.16	0.86	0.87	0.75	0.51	1.05	0.78	1.67	0.67
Sulphur trioxide (SO_3)	4.67	1.60	1.76	0.21	0.08	1.75	0.65	0.42	1.52
Loss on ignition	2.09	2.44	2.36	0.32	0.27	0.75	3.34	2.10	0.32

Table 3
Grading of aggregates

Coarse aggregate		Fine aggregate	
Sieve size (mm)	Cumulative percentage retained	Sieve size (mm)	Cumulative percentage retained
19.0	0.0	4.75	0.0
12.7	40.0	2.36	10.0
9.5	65.0	1.18	32.5
4.75	100.00	0.60	57.5
–	–	0.30	80.0
–	–	0.15	94.0
–	–	pan	100.0

concrete, i.e. temperature, slump, air content, and density were determined, and are shown in Table 5.

4. Casting of test specimens

A total of 18 100 × 200-mm cylinders were cast from each mixture. The cylinders were consolidated on a vibrating table. After casting, the cylinders were covered with a wet burlap and left in the casting room for 24 h. Following this, the cylinders were demoulded and transferred to the moist curing room 23 ± 1.7°C until required for testing.

5. Compressive strength determination of test cylinders

The concrete cylinders were tested for compressive strength at 1, 3, 7, 28, 56, and 91 days. Before testing, the cylinders were capped using a proprietary capping compound.

6. Discussion of the test results

6.1. Chemical composition of fly ash

The analytical CaO content of the fly ashes covered a wide range from 0.31% (Belledune) to 15.81% (Thunder Bay). Incidentally, the highest equivalent alkali content ($Na_2O + 0.658\ K_2O$) was also for the fly ash from Thunder Bay. For Sundance, Forestburg, and Coal Creek fly ashes, the alkali contents were between 3.78% and 4.64%; for other fly ashes the values were less than 2.60%. The loss on ignition for all the fly ashes was generally low with a highest value of 3.34% for the fly ash from Belledune.

The water demand of the mortars incorporating fly ashes ranged from 93% to 98% of the control mixture.

The fly ashes investigated were generally very fine and the percentage of particles retained on 45-μm sieve ranged from 23.9% to 10.3%, the lowest value being for the fly ash from Thunder Bay.

6.2. Reduction in water demand of concrete incorporating fly ash

As mentioned earlier, no air-entraining admixture, water-reducing admixture, or superplasticizer was used in the concrete mixtures. The water-reduction in the concrete mixture incorporating fly ash as compared to the control mixture was primarily due to the physical characteristics of the fly ashes used. The percentage of reduction in water in fly ash concrete mixtures compared to the control mixture ranged from a low 8.8% for Lingan fly ash to a high of 19.4% for Coal Creek fly ash. These water reduction values are significant especially for Coal Creek (19.4%), Thunder Bay (18.8%), and Forestburg (17.6%) fly ashes. Thus, the requirement for superplasticizers to achieve high slumps in concrete will be reduced considerably when these fly ashes are to be used in HVFA concrete. For the fly ashes from

Table 4
Mixture proportions of concrete

Mixture no.	Fly ash	F/(C + F) (%)	W/(C + F)	Quantities (kg/m^3)				
				Water	Cement	Fly ash	Fine aggregate	Coarse aggregate
F0	–	0	0.43	170	396	0	740	1110
F1	Point Tupper	55	0.38	151	181	221	742	1113
F2	Lingan	55	0.39	155	180	220	745	1117
F3	Sundance	55	0.37	146	180	220	726	1089
F4	Forestburg	55	0.35	140	182	222	727	1090
F5	Thunder Bay	55	0.34	138	182	222	749	1124
F6	Belledune	55	0.38	154	181	222	740	1110
F7	Belews Creek	55	0.38	152	179	219	731	1097
F8	Coal Creek	55	0.34	137	182	222	749	1124

Table 5
Properties of the fresh concrete

Mixture no.	Fly ash	F/(C+F) (%)	W/(C+F)	Water reduction (%)	Temperature (°C)	Density (kg/m^3)	Slump (mm)	Air content (%)
F0	–	0	0.43	–	23.0	2444	57	1.9
F1	Point Tupper	55	0.38	11.2	23.0	2429	57	1.9
F2	Lingan	55	0.39	8.8	23.0	2444	57	2.0
F3	Sundance	55	0.37	14.1	23.0	2415	64	1.9
F4	Forestburg	55	0.35	17.6	21.5	24.01	57	1.7
F5	Thunder Bay	55	0.34	18.8	21.0	2415	57	1.9
F6	Belledune	55	0.38	9.4	22.0	2401	70	1.8
F7	Belews Creek	55	0.38	10.6	22.0	2387	57	1.8
F8	Coal Creek	55	0.34	19.4	21.5	2415	64	2.0

Table 6
Compressive strength

Mixture no.	Fly ash	F/(C+F) (%)	W/(C+F)	Compressive strength, MPa[a]					
				1 day	3 days	7 days	28 days	56 days	91 days
F0	–	0	0.43	26.8	34.0	39.5	50.7	54.2	57.7
F1	Point Tupper	55	0.38	10.3	17.1	22.7	34.9	43.1	48.0
F2	Lingan	55	0.39	8.8	15.1	21.2	32.7	40.2	44.7
F3	Sundance	55	0.37	8.7	22.4	31.8	53.0	62.1	65.2
F4	Forestburg	55	0.35	7.9	19.6	26.9	42.9	51.3	56.1
F5	Thunder Bay	55	0.34	13.9	30.1	42.2	55.8	58.2	61.9
F6	Belledune	55	0.38	6.9	15.7	20.8	31.8	39.0	43.9
F7	Belews Creek	55	0.38	6.3	13.9	18.0	30.7	37.7	44.6
F8	Coal Creek	55	0.34	10.3	23.4	31.1	47.5	55.7	60.0

[a] Average of three 100 × 200-mm cylinders.

other sources, high dosages of superplasticizers will be required to achieve high slumps in HVFA concrete.

As mentioned earlier, no air-entraining admixture was used in the concrete mixtures. Thus, further water reductions can be achieved if air-entraining admixtures are incorporated into the concrete because for each percentage of air content, there is a reduction in water demand of about 2%. However, the use of air-entraining admixtures will affect adversely the strength properties of concrete [3].

6.3. Compressive strength development

The compressive strength of the concrete mixtures investigated are shown in Table 6. Notwithstanding that early-age (1-day) strength of HVFA concrete are lower than that of the control concrete, they are adequate for form work removal between 1 and 2 days. At 28 and 91 days, the compressive strength for all the HVFA concrete was greater than 30 and 40 MPa, respectively. For concrete incorporating fly ashes from Thunder Bay and Sundance, the 28-day strength was > 50 MPa, and was comparable to that of the control Portland cement concrete.

6.4. Relationship between various characteristics of fly ash and compressive strength of concrete

No attempt has been made to correlate various individual parameters of fly ashes with compressive strength of concrete incorporating these fly ashes because these correlations are not considered useful in practice and their use is discouraged; however, it should be mentioned that several researchers have been moderately successful in establishing the above mentioned correlations [4–6].

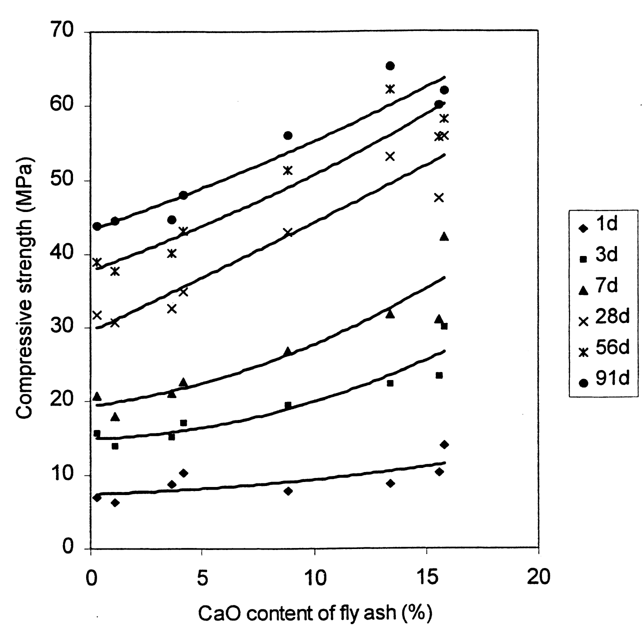

Fig. 1. Compressive strength vs. CaO content of fly ash.

There appears to be a relationship between the CaO content of fly ash and the compressive strength of concrete (Fig. 1). However, fly ashes with high CaO also have high alkali content and this can also affect strengths. The examples are fly ashes from Thunder Bay, Coal Creek, and Sundance. The fineness of fly ash also affects the compressive strength.

7. Conclusions

The results of this investigation show that significant reduction in water demand can be achieved due to the incorporation of fly ash in non-air-entrained, high-volume fly ash concrete. These reductions in water demand range from 8.8% for concrete made with fly ash from Lingan, Nova Scotia to 19.4% for concrete incorporating fly ash from Coal Creek, the USA.

The concrete mixtures investigated had slumps ranging from 57 to 70 mm. In order to achieve slumps >100 mm while still maintaining the same strength as before, it will be necessary to use water-reducers or superplasticizers in the concrete.

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