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Optimization of fly ash content in concrete
Part I: Non-air-entrained concrete made without superplasticizer

N. Bouzoubaâ*, B. Fournier

International Centre for Sustainable Development of Cement and Concrete (ICON), CANMET/Natural Resources Canada, 405 Rochester Street, Ottawa, ON, Canada K1A 0G1

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Abstract

This paper outlines the preliminary results of a research project aimed at optimizing the fly ash content in concrete. Such fly ash concrete would develop an adequate 1-day compressive strength and would be less expensive than the normal Portland cement concrete with similar 28-day compressive strength. The results show that, in a normal Portland cement concrete having a 28-day compressive strength of 40 MPa, it is possible to replace 50% of cement by a fine fly ash (~ 3000 cm^2/g) with a CaO content of ~ 13%, yielding a concrete of similar 28-day compressive strength. This concrete can be designed to yield an early-age strength of 10 MPa and results in a cost reduction of about 20% in comparison to the control concrete. In a case of a coarser fly ash (~ 2000 cm^2/g) with a CaO content of ~ 4%, substitution levels of cement by this ash could be from 30% to 40%. This concrete yields a 1-day compressive strength of 10 MPa and a 28-day compressive strength similar to that of the control concrete. The total cost of this concrete is about 10% lower than that of the control concrete.

Keywords: Fly ash; Compressive strength; Statistical analysis; Cost

1. Introduction

High-volume fly ash (HVFA) concrete was developed by CANMET in the 1980s. In this high-performance concrete, 55–60% of the Portland cement is replaced by ASTM Class F fly ash. The water-to-cementitious materials ratio (W/CM) is maintained at 0.30 ± 0.02 with Portland cement and fly ash contents at about 150 and 225 kg/m^3, respectively. The water content of the mixture is kept low at about 120 kg/m^3, and acceptable workability is achieved by large dosages of a superplasticizer (SP), typically 3 to 6 l/m^3. This type of concrete has excellent long-term durability and mechanical properties, and this has been supported by voluminous research data and some field data [1–12]. The early-age strength (6 to 8 MPa) at 1 day is ample enough for formwork removal except in cold regions. The later-age strength of more than 110 MPa at 10 years has been achieved in demonstration blocks [13].

This research project, aimed at optimizing the fly ash content in concrete, was initiated in order to extend the general concept of HVFA concrete and its applications to a wider range of infrastructure construction. Such fly ash concrete would develop an adequate 1-day compressive strength and have economical advantages compared to conventional Portland cement concrete with similar 28-day compressive strength.

The objective of this study was to determine the optimum amount of fly ash in non-air-entrained and nonsuperplasticized concrete yielding a similar 28-day compressive strength to that of a control concrete made with Portland cement only. The control concrete was a non-air-entrained concrete with a cement content of 330 kg/m^3, a water-to-cement ratio of 0.50, and a 28-day compressive strength of 40 MPa. For the fly ash concrete, the cement replacement range by fly ash was 30% to 50% of the total weight of the CM (cement+fly ash), which was kept at 300 to 400 kg/m^3. The water was adjusted to have a fly ash concrete with a slump of 100 ± 20 mm.

* Corresponding author. Tel.: +1-613-992-6153; fax: +1-613-992-9389.

E-mail address: bouzouba@nrcan.gc.ca (N. Bouzoubaâ).

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Table 1
Physical properties and chemical analyses of the materials used

	ASTM Type I cement	Fly ash	
		Sundance	Point Tupper
Physical tests			
Specific gravity	3.15	2.08	2.58
Fineness			
Passing 45 μm (%)	94.0	83.6	75.2
Specific surface, Blaine (cm^2/g)	4100	3060	2270
Compressive strength of 51-mm cubes (MPa)			
7-day	26.0	–	–
28-day	31.9	–	–
Water requirement (%)	–	99.2	95.6
Pozzolanic activity index (%)			
7-day	–	94.5	79.6
28-day	–	106.9	89.2
Time of setting, Vicat test (min)			
Initial setting	220	–	–
Final setting	325	–	–
Air content of mortar (vol. %)	5.5	–	–
Chemical analyses (%)			
Silicon dioxide (SiO_2)	20.3	52.4	42.7
Aluminium oxide (Al_2O_3)	4.2	23.4	20.3
Ferric oxide (Fe_2O_3)	3.0	4.7	23.7
Calcium oxide (CaO)	62.0	13.4	4.2
Magnesium oxide (MgO)	2.8	1.3	1.2
Sodium oxide (Na_2O)	0.3	3.6	0.9
Potassium oxide (K_2O)	0.9	0.6	2.6
Equivalent alkali ($Na_2O + 0.658K_2O$)	0.9	4.0	2.6
Phosphorous oxide (P_2O_5)	0.2	0.2	0.7
Titanium oxide (TiO_2)	0.2	0.8	0.9
Sulphur trioxide (SO_3)	3.5	0.2	1.6
Loss on ignition	2.0	0.3	2.4
Bogue potential compound composition			
Tricalcium silicate (C_3S)	55.6	–	–
Dicalcium silicate (C_2S)	16.3	–	–
Tricalcium aluminate (C_3A)	6.1	–	–
Tetracalcium aluminoferrite (C_4AF)	9.1	–	–

To achieve these objectives, a statistical program was used to optimise the number of concrete mixtures. Seventeen concrete mixtures were therefore tested in this program. These included one control concrete with ASTM Type I cement and 16 fly ash concrete mixtures using two fly ashes. For each fly ash, two concrete mixtures were made with a CM content of 300 kg/m^3 and a fly ash content of 30% and 50%, two concrete mixtures with a CM content of 400 kg/m^3 and a fly ash content of 30% and 50%, and four similar concrete mixtures with a CM content of 350 kg/m^3 and a fly ash content of 40% to verify the repeatability of the results. All concrete mixtures included a water-reducing admixture. The compressive strength for each concrete was determined on three cylinders at 1, 7, 28, and 56 days.

2. Materials

2.1. Cement

ASTM Type I Portland cement was used. Its physical properties and chemical compositions are presented in Table 1.

2.2. Fly ash

Fly ashes from Point Tupper, Nova Scotia and Sundance, Alberta were used in this study. Their physical properties and chemical compositions are also given in Table 1.

Point Tupper fly ash, an ASTM Class F ash, contained 4.2% CaO and a high Fe_2O_3 content of 23.7%. The ash had a Blaine fineness of 2270 cm^2/g and a specific gravity of 2.58. The relatively high specific gravity of the fly ash is, to a large extent, related to its high iron content.

Sundance fly ash met the general requirements of ASTM Class F ash, had relatively high CaO content of 13.4% and alkali content (Na_2O equivalent) of 4.0%. The Blaine fineness of the ash was 3060 cm^2/g and the specific gravity was 2.08.

2.3. Admixtures

A water-reducing admixture composed of modified polymers and lignosulfonates (WR) was used in all the concrete mixtures.

2.4. Aggregates

Crushed limestone with a maximum nominal size of 19 mm was used as the coarse aggregate, and a local natural sand derived from granite was used as the fine aggregate in the concrete mixtures. The coarse aggregate was separated into different size fractions and recombined to a specific grading shown in Table 2. The coarse and fine aggregates each had a specific gravity of 2.70 and water absorptions of 0.4% and 0.8%, respectively.

3. Mixture proportions

The proportions of the concrete mixtures are summarized in Table 3. For all the mixtures, the coarse and fine aggregates were weighed in a dry room condition. The coarse aggregate was then immersed in water for 24 h. The excess water was decanted and the water retained by the aggregates was determined by the weight difference. A

Table 2
Grading of coarse aggregate

Sieve size (mm)	Passing (%)
19.0	100
12.7	67
9.5	34
4.75	0

Table 3
Proportions of the concrete mixtures

Mixture no.	W/CM[a]	Water	Cement (kg/m^3)	Fly ash			CM[a] (kg)	Fine aggregate (kg/m^3)	Coarse aggregate (kg/m^3)	WR[b] (ml/m^3)
				Type	%	kg/m^3				
1	0.50	165	331	–	0	0	~330	768	1153	1159
2	0.53	157	207	Sundance	30	89	~300	786	1178	741
3	0.46	139	150		50	150		797	1195	526
4	0.42	163	273		30	117	~400	746	1118	954
5	0.38	155	202		50	202		744	1114	706
6	0.43	154	214		40	143	~350	768	1152	750
7	0.43	153	213			142		763	1146	746
8	0.43	153	213			142		763	1146	746
9	0.43	153	213			142		763	1146	746
10	0.52	159	213	Point Tupper	30	91	~300	781	1172	745
11	0.5	151	150		50	150		792	1187	527
12	0.44	174	274		30	117	~400	742	1109	960
13	0.39	161	204		50	204		745	1116	715
14	0.44	157	215		40	143	~350	768	1149	751
15	0.44	157	215			143		768	1149	751
16	0.46	162	211			141		767	1150	740
17	0.44	157	215			143		768	1149	751

[a] Cement + fly ash.
[b] Water reducer (350 ml/100 kg of cement).

predetermined amount of water was added to the fine aggregate that was then allowed to stand for 24 h.

4. Preparation and casting of test specimens

All the concrete mixtures were mixed for 5 min in a laboratory countercurrent mixer. From each concrete mixture, twelve 100 × 200-mm cylinders were cast for the determination of the compressive strength.

The specimens were cast in two layers and were compacted on a vibrating table. After casting, all the molded specimens were covered with plastic sheets and water-saturated burlap and left in the casting room for 24 h. They were then demolded and the cylinders were transferred to the moist-curing room at 23 ± 2 °C and 100% relative humidity until required for testing.

5. Testing of the specimens

The slump and air content of fresh concrete were determined following ASTM standards. For each mixture, the compressive strength was determined on three cylinders at 1, 7, 28, and 56 days according to ASTM C 39.

6. Results and discussion

6.1. Properties of fresh concrete

The unit weight, slump, and air content of the fresh concrete are given in Table 4. The slump of the control concrete was 100 mm and that of fly ash concrete ranged from 80 to 120 mm. For the fly ash concrete, the water was adjusted to have a concrete with a slump of 100 ± 20 mm. Thus, the W/CM ratio of the fly ash concrete ranged from 0.43 to 0.53. The water demand of the fly ash concrete decreased with both increased fly ash content and increased total weight of CM. In general, the Point Tupper fly ash concrete required more water than the Sundance fly ash concrete although the water requirement test of the Sundance ash presented higher value than that of the Point Tupper ash (Table 1). The entrapped air content of the concrete ranged from 1.2% to 2%.

6.2. Compressive strength

The compressive strengths of the different concretes are shown in Table 5. The control concrete developed compressive strengths of 19.4, 32.6, 40.1, and 43.0 MPa at 1, 7, 28, and 56 days, respectively. The fly ash concrete developed compressive strengths ranging from 3.4 to 18.5, 15.3 to 36.5, 28.0 to 56.0, and 34.0 to 62.0 MPa at 1, 7, 28, and 56 days, respectively.

The compressive strength increased with a decrease in the fly ash content and an increase in the CM content. In line with the results of the strength activity index of the fly ashes, the Sundance fly ash concrete developed higher compressive strengths than those of the Point Tupper fly ash concrete, which is mainly due to the high fineness and CaO content of Sundance fly ash (Table 1).

6.3. Statistical analysis

Easy state, a statistical program, was used to analyse the results. The objective of the study was to determine a less expensive concrete mixture incorporating the highest pos-

Table 4
Properties of the fresh concrete

Mixture no.	W/CM[a]	Fly ash		CM[a] (kg)	Unit weight (kg/m^3)	Slump (mm)	Air content (%)
		Type	%				
1	0.50	–	0	~330	2418	100	2.0
2	0.53	Sundance	30	~300	2418	110	1.2
3	0.46		50		2432	90	1.3
4	0.42		30	~400	2418	90	1.6
5	0.38		50		2418	90	1.4
6	0.43		40	~350	2432	90	1.6
7	0.43				2418	90	1.7
8	0.43				2418	100	1.6
9	0.43				2418	95	1.8
10	0.52	Point Tupper	30	~300	2418	110	1.7
11	0.50		50		2432	90	1.4
12	0.44		30	~400	2418	120	1.5
13	0.39		50		2432	105	1.5
14	0.44		40	~350	2432	90	1.7
15	0.44				2432	90	1.7
16	0.46				2432	110	1.3
17	0.44				2432	80	1.6

[a] Cement + fly ash.

sible percentage of fly ash that would develop similar strength as the normal Portland cement concrete.

6.3.1. Sundance fly ash

Fig. 1 shows the isostrength contour lines of the Sundance fly ash concrete at 1, 7, 28, and 56 days.

The 1- and 7-day isostrength contour lines of the Sundance fly ash concrete show that for similar CM content, the compressive strength decreased with increasing fly ash content in the concrete mixture; however, at 28 and 56 days, the effect of the fly ash on the compressive strength was negligible. The results confirmed the fact that the strength development of the fly ash concrete is rather slow and that the pozzolanic contribution of the fly ash to the strength generally appears after 7 days of curing.

Fig. 1 also indicates the various combinations of CM and fly ash contents in a linear relationship for each 1-, 7-, 28-, and 56-day compressive strength. The results show that, for example, if 10 MPa is the minimum 1-day compressive strength required for applications that need fast formwork removal, concrete mixtures with combinations of CM and fly ash contents ranging from 300 kg/m^3 CM with 35% fly ash to 365 kg/m^3 with 50% fly ash would meet the above criterion (Fig. 1). If the concrete was to be used in a high-

Table 5
Compressive strength of concrete

Mixture no.	W/CM[a]	Fly ash		CM[a] (kg)	Density of hardened concrete (1-Day) (kg/m^3)	Compressive strength (MPa)				Cost[b] (Can$)
		Type	%			1-day	7-day	28-day	56-day	
1	0.50	–	0	~330	2311	19.4	32.6	40.1	43	43.03
2	0.53	Sundance	30	~300	2425	11.5	25	42.5	49	32.69
3	0.46		50		2430	5.9	21.8	41.8	47	29.25
4	0.42		30	~400	2419	18.5	36.5	56	61	43.09
5	0.38		50		2419	12.3	34.6	55.7	62	39.39
6	0.43		40	~350	2435	10.5	29.7	52.7	60	37.11
7	0.43				2414	10.4	30.8	53	59	36.92
8	0.43				2429	11	30.8	53.4	58	36.92
9	0.43				2414	10.8	31.5	50.6	59	36.92
10	0.52	Point Tupper	30	~300	2428	7.2	22.5	35.9	41	33.6
11	0.5		50		2445	3.4	15.3	28	34	29.25
12	0.44		30	~400	2419	11.7	31.5	44.6	50	43.22
13	0.39		50		2425	8	25.9	43.8	51	39.78
14	0.44		40	~350	2426	10.3	26.5	42	49	37.24
15	0.44				2421	10.8	27.6	42.5	49	37.24
16	0.46				2439	9	25.5	39	47	36.59
17	0.44				2420	10.1	27.3	43.5	49	37.24

[a] Cement + fly ash.
[b] The cost is based on the price of the cementitious materials used, i.e., Can$130/tonne for cement and Can$65/tonne for fly ash.

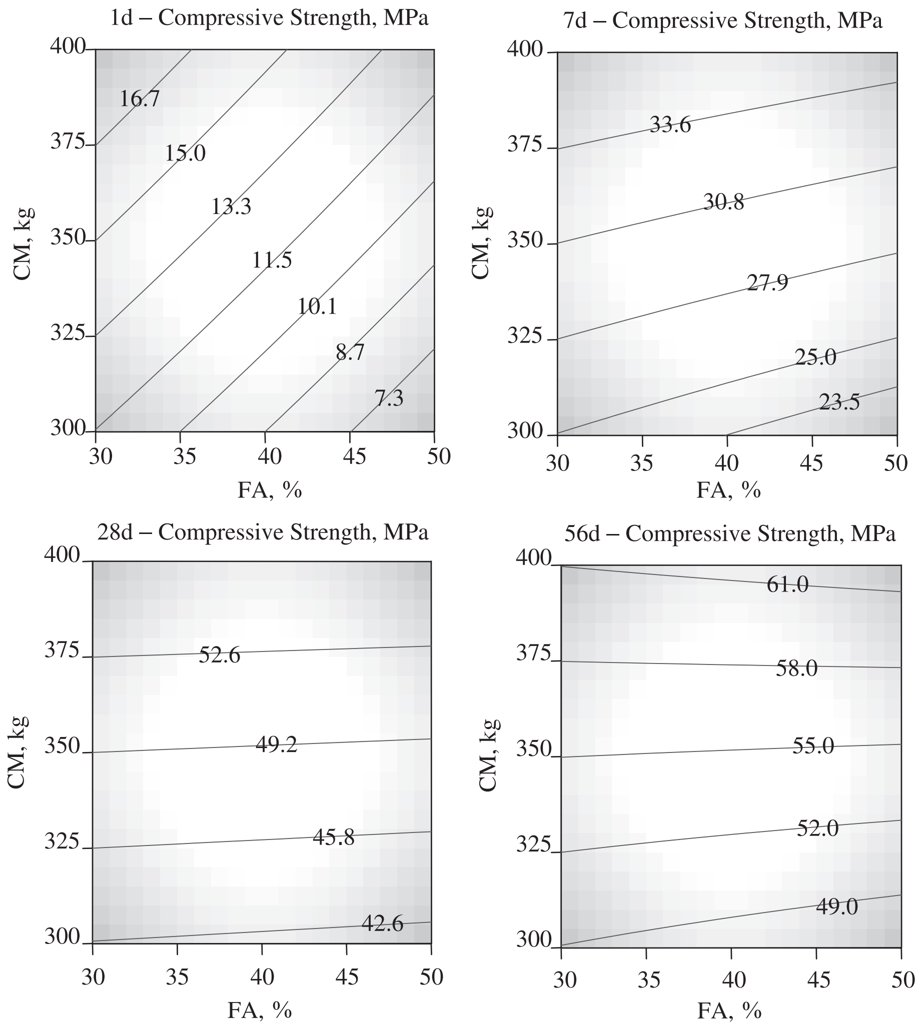

Fig. 1. Isostrength lines of Sundance fly ash concrete.

rise structure where a minimum of 16 MPa is generally required for a 1-day compressive strength, concrete mixtures with combinations of CM and fly ash contents ranging from 370 kg/m^3 CM with 30% fly ash to 400 kg/m^3 CM with 37% Sundance fly ash would meet that criterion.

6.3.2. Cost analysis

Fig. 2 presents the isocost contour lines of the Sundance fly ash concrete mixtures superimposed to the isostrength contour lines of these concrete mixtures at 1, 7, 28, and 56 days. The prices used in the present study were Can$130/tonne for cement and Can$65/tonne for fly ash. The price of the materials will change depending on the location; therefore, the following observations should not be generalized.

Fig. 2 shows that the slope of the isocost contour lines was lower than that of the isostrength lines at 1 day, but higher than those of the isostrength lines at 7, 28, and 56 days. Therefore, the less expensive concrete mixture proportions that satisfy a criterion related to a 1-day compressive strength would be those made with lower fly ash contents. Whereas, the less expensive concrete mixture proportions that satisfy a criterion related to 7-, 28-, or 56-day compressive strength would be those made with higher fly ash contents. For example, the less expensive concrete mixture that developed compressive strength of 10 MPa at 1 day was that made with 300 kg of CM and incorporating 35% of fly ash compared to that made with more CM and incorporating more fly ash. On the other hand, the less expensive concrete mixture that developed compressive strength of 42.6 MPa at 28 days was that made with 306 kg of CM and incorporating 50% of fly ash compared to that made with less CM and incorporating less fly ash.

Table 5 shows that the less expensive Sundance fly ash concrete mixture that developed a similar 28-day compressive strength as that of the control concrete is that made with 300 kg of CM and incorporating 50% of fly ash. Its cost was approximately Can$14 (or ~30%) less than that of the control concrete, but it developed a 1-day compressive strength of only 5.9 MPa.

The fly ash concrete that developed a similar 1-day compressive strength as that of the control concrete was

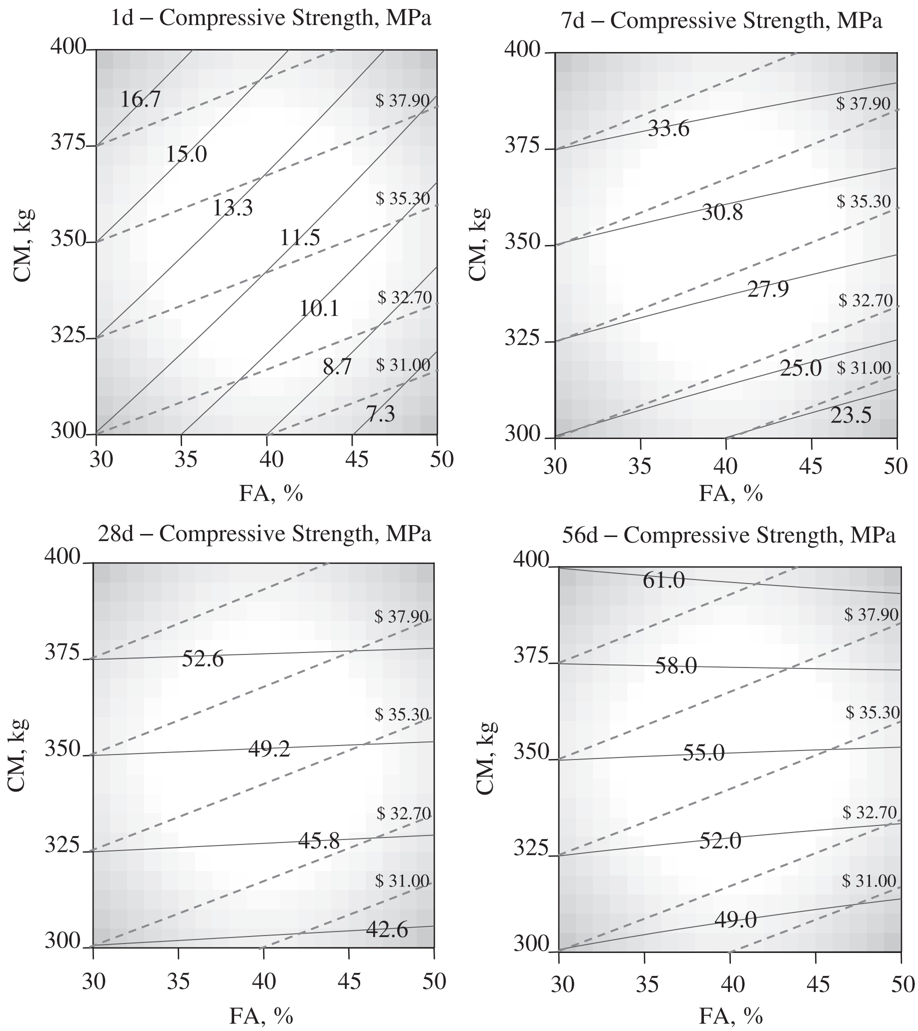

Fig. 2. Isocost lines superimposed to isostrength lines of Sundance fly ash concrete. The solid line corresponds to compressive strength; the dashed line corresponds to the cost, in Canadian dollars.

that made with 400 kg of CM and incorporating 30% of fly ash. The cost of the fly ash concrete was also similar to that of the control concrete (i.e., about Can$43), but the fly ash concrete developed a 28-day compressive strength of 56 MPa that was 40% higher than that of the control concrete. Therefore, with an ASTM Class F fly ash of Sundance quality (Blaine fineness of ~ 3000 cm^2/g and a content of CaO higher than 10%), one can proportion a concrete that incorporates up to 50% of the fly ash and develops 1- and 28-day compressive strengths higher than 10 and 40 MPa, respectively. Such concrete would also cost less than a normal Portland cement concrete with a 28-day compressive strength of 40 MPa.

6.3.3. Point Tupper fly ash

Fig. 3 presents the isostrength contour lines of the Point Tupper fly ash concrete at 1, 7, 28, and 56 days. The results show once again that the strength development of the fly ash concrete is slow. However, for Point Tupper fly ash, the contribution of the fly ash to the compressive strength development of the concrete appeared to be more significant at 56 days in comparison to the 28 days for Sundance fly ash; this is probably due to the high reactivity of the Sundance fly ash.

Fig. 3 also shows the various combinations of CM and fly ash contents required for a concrete mixture to achieve a certain compressive strength at 1, 7, 28, and 56 days. For example, for a minimum 1-day compressive strength requirement of 10 MPa, the combinations of CM and fly ash contents would range from 370 kg/m^3 CM with 30% fly ash to 400 kg/m^3 CM with 37.5% fly ash. However, it should be noted that according to the experimental results (Table 5), Point Tupper fly ash concrete made with CM content of 350 kg/m^3 and incorporating 40% of fly ash satisfied the above criterion as well. This indicates that the statistical model is conservative and might overestimate the weight of CM or underestimate the fly ash content.

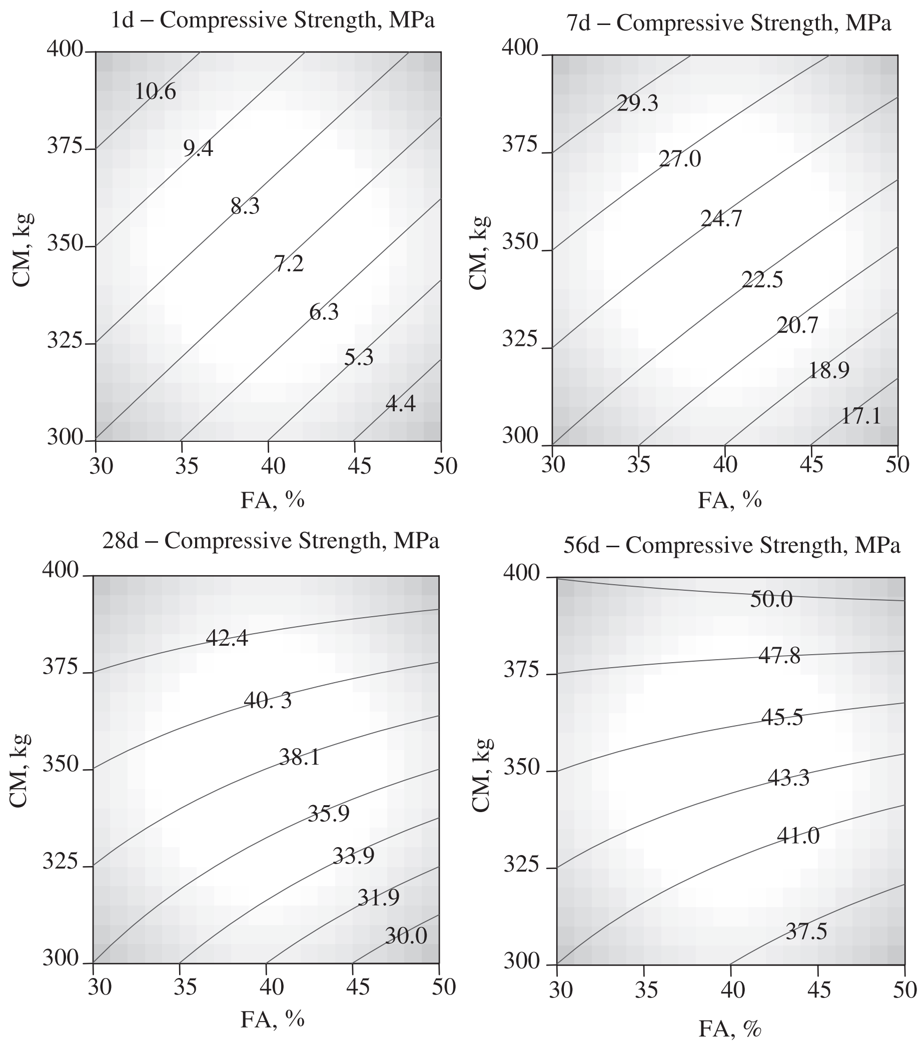

Fig. 3. Isostrength lines of Point Tupper fly ash concrete.

6.3.4. Cost analysis

Fig. 4 presents the isocost contour lines of the Point Tupper fly ash concrete mixtures superimposed to the isostrength contour lines of these concrete mixtures at 1, 7, 28, and 56 days. Fig. 4 shows that the slope of the isocost contour lines was lower than that of the isostrength lines at 1 and 7 days, and at 28 days for compressive strength below 40 MPa. Therefore, the less expensive concrete mixture proportions that satisfy a criterion related to 1-, 7-, and 28-day compressive strength would be that made with lower fly ash content within the range of 30% to 50%. However, when comparing the cost of fly ash concrete to concrete made with Portland cement only, Table 5 shows that the less expensive Point Tupper fly ash concrete that developed a 1-day compressive strength of 10 MPa and a 28-day compressive strength similar to that of the control concrete was that made with 350 kg of CM and incorporating 40% of fly ash. The cost of the fly ash concrete was approximately Can$6 (or ~14%) less than that of the control concrete.

Therefore, for an ASTM Class F fly ash with similar properties to that of Point Tupper fly ash, one can proportion a concrete with 350 kg/m^3 of CM and incorporating up to 40% of the fly ash, which develops adequate 1- and 28-day compressive strengths. The fly ash concrete would still be less expensive than the conventional Portland cement concrete with a 28-day compressive strength of 40 MPa.

7. Conclusion

The above investigation shows that it is possible to proportion a nonsuperplasticized fly ash concrete with a total CM content ranging from 300 to 400 kg/m^3 and incorporating up to 50% of fly ash that could develop an adequate 1-day compressive strength, a 28-day compressive strength higher than 40 MPa, and that would be more competitive in terms of cost than conventional Portland cement concrete.

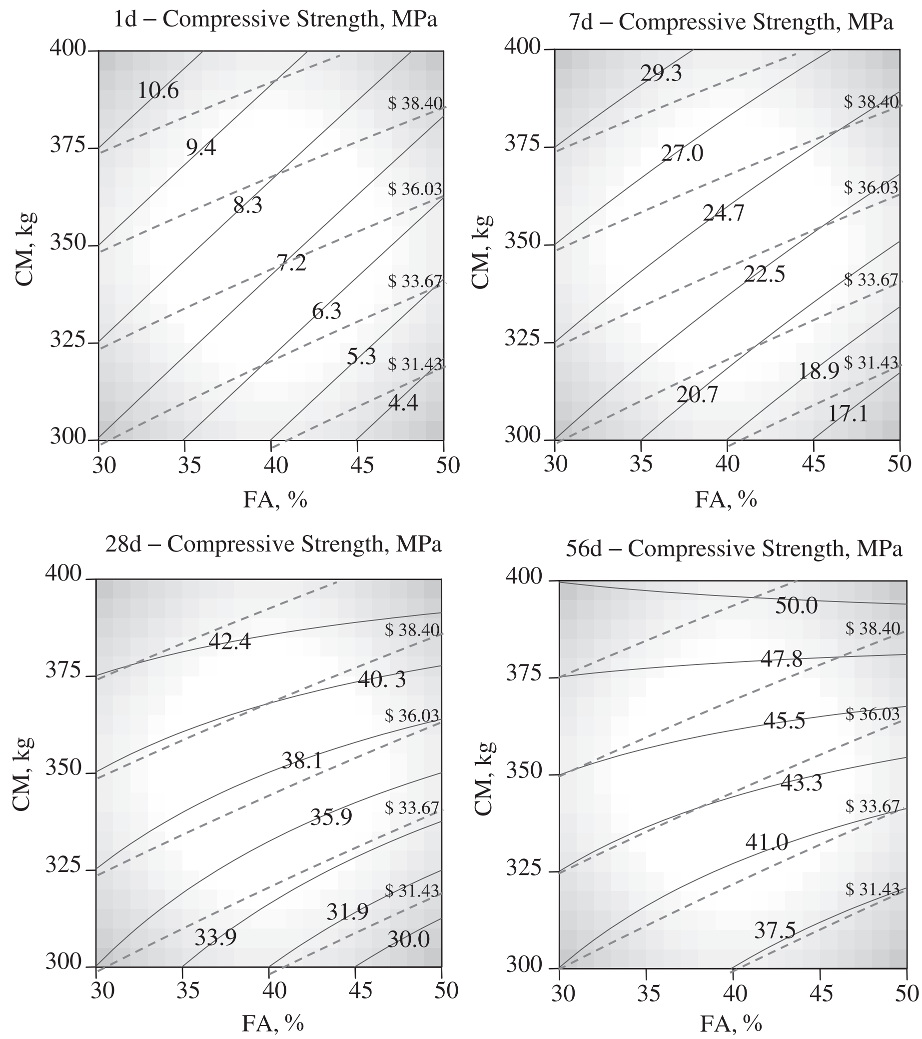

Fig. 4. Isocost lines superimposed to isostrength lines of Point Tupper fly ash concrete. The solid line corresponds to compressive strength; the dashed line corresponds to the cost, in Canadian dollars.

For the Sundance fly ash, it is possible to substitute a non-air-entrained conventional Portland cement concrete having a 1-day compressive strength of ~20 MPa with a fly ash concrete incorporating 30% of fly ash and having a similar 1-day strength and cost. However, such fly ash concrete would develop a higher 28-day compressive strength than that of conventional Portland cement concrete. If the 1-day compressive strength is not an issue, the above control concrete could be substituted with a similar 28-day compressive strength fly ash concrete (~40 MPa) incorporating 300 kg of CM and 50% of fly ash; the latter would be significantly less expensive (~30%) than the control concrete. The above savings on materials costs could also be used for the addition of a SP to enhance the early-age compressive strength of the fly ash concrete, thus, leading to the CANMET HVFA concrete system. Such concrete would then have additional benefits such as extremely low permeability and increased long-term durability.

For the Point Tupper fly ash, it is possible to substitute the above control concrete with a similar 28-day compressive strength fly ash concrete made with 350 kg of CM and incorporating 40% of fly ash. Such fly ash concrete would develop a 1-day compressive strength of approximately 10 MPa and would cost less (~14%) than the control concrete.

References

[1] V.M. Malhotra, Superplasticized fly ash concrete for structural applications, Concr. Int. 8 (12) (1986 December) 28–31.

[2] G.M. Giaccio, V.M. Malhotra, Concrete incorporating high volumes of ASTM Class F fly ash, Cem., Concr. Aggreg. 10 (12) (1988) 88–95.

[3] V.M. Malhotra, K.E. Painter, Early-age strength properties and freezing and thawing resistance of concrete incorporating high volumes of ASTM Class F fly ash, Int. J. Cem. Compos. Lightweight Concr. 11 (1) (1989) 37–46.

[4] W.S. Langley, G.G. Carette, V.M. Malhotra, Structural concrete incorporating high volumes of ASTM Class F fly ash, ACI Mater. J. 86 (5) (1989) 507–514.

[5] V. Sivasundaram, G.G. Carette, V.M. Malhotra, Properties of concrete incorporating low quantity of cement and high volumes of low calcium fly ash, in: V.M. Malhotra (Ed.), ACI SP-114, vol. 1, 1989, pp. 45–71.

[6] V. Sivasundaram, G.G. Carette, V.M. Malhotra, Long-term strength development of high-volume fly ash concrete, Cem. Concr. Compos. 12 (4) (1990) 263–270.

[7] V. Sivasundaram, G.G. Carette, V.M. Malhotra, Mechanical properties, creep, and resistance to diffusion of chloride ions of concrete incorporating high volumes of ASTM Class F fly ashes from seven different sources, ACI Mater. J. 88 (4) (1991) 407–416.

[8] M.M. Alasali, V.M. Malhotra, Role of concrete incorporating high volumes of fly ash in controlling expansion due to alkali–aggregate reaction, ACI Mater. J. 88 (2) (1991) 159–163.

[9] A. Bilodeau, V.M. Malhotra, Concrete incorporating high volumes of ASTM Class F fly ashes: mechanical properties and resistance to deicing salt scaling and to chloride-ion penetration, in: V.M. Malhotra (Ed.), ACI SP-132, vol. 1, 1992, pp. 319–349.

[10] G.G. Carette, A. Bilodeau, R.L. Chevrier, V.M. Malhotra, Mechanical properties of concrete incorporating high volumes of fly ash from sources in the U.S., ACI Mater. J. 90 (6) (1993) 535–544.

[11] A. Bilodeau, V. Sivasundaram, K.E. Painter, V.M. Malhotra, Durability of concrete incorporating high volumes of fly ash from sources in the U.S., ACI Mater. J. 91 (1) (1994) 3–12.

[12] A. Bilodeau, V.M. Malhotra, High-volume fly ash system: concrete solution for sustainable development, ACI Mater. J. 97 (1) (2000) 41–48.

[13] V.M. Malhotra, Making concrete "greener" with fly ash, Concr. Int. 21 (5) (1999) 61–66.