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Optimization of Fly Ash Content in Concrete

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Abstract

This report 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, air-entrained or not, 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 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. The above fly ash concrete are made without the use of a superplasticizer, and are found to have higher resistance to chloride-ion penetration than the control concrete.

Introduction

High-volume fly ash (HVFA) concrete was developed by CANMET in the 1980's. 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 mechanical and durability properties and this has been supported by voluminous research data and some field data (1-19). The early-age strength (6 to 8 MPa) at 1 day is ample enough for form work removal except in cold regions. The later-age strength of more than 110 MPa at 10 years has been achieved in demonstration blocks (20).

In order to extend the general concept of HVFA concrete and its applications to a wider range of infrastructure construction, this research project was initiated, aimed at optimizing the fly ash content in concrete. 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.

Part I: Non air-entrained fly ash concrete

The objective of Part I of this study was to determine the optimum amount of fly ash in non air-entrained and non-superplasticized concrete yielding 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 cementitious materials (CM) 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.

In order to achieve the above 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 sixteen 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, and for each concrete, the compressive strength was determined on three cylinders at 1, 7, 28, and 56 days.

Materials

Cement

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

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.

Admixtures

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

Aggregates

Crushed limestone derived from granite with a maximum nominal size of 19 mm was used as the coarse aggregate, and a local natural sand 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.

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 room dry condition. The coarse aggregate was then immersed in water for 24 hours. The excess water was decanted, and the water retained by the aggregates was determined by the weight difference. A predetermined amount of water was added to the fine aggregate that was then allowed to stand for 24 hours.

Preparation and Casting of Test Specimens

All the concrete mixtures were mixed for five minutes in a laboratory counter-current mixer. From each concrete mixture, twelve 100H200-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 hours. They were then demolded and the cylinders were transferred to the moist-curing room at 23 ∀ 2EC and 100 % relative humidity until required for testing.

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.

Results and Discussion

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 water-to-cementitious materials 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 cementitious materials. In general, the Point-Tupper fly ash concrete required more water than 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%.

Compressive strength

The compressive strength of the different concrete 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 from 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. The Sundance fly ash concrete developed higher compressive strengths than those of the Point-Tupper fly ash concrete, and this is in line with the results of the strength activity index of the fly ashes, that is mainly due to the high fineness and CaO content of Sundance fly ash (Table 1).

Statistical analysis

Easy state, a statistical program was used to analyse the results. The objective of the study was to determine a concrete mixture incorporating the highest possible percentage of fly ash that would develop similar strength as for the normal portland-cement concrete, and at the same time would cost less.

<u>Sundance fly ash</u>

Figure 1 shows the iso-strength contour lines of the Sundance fly ash concrete at 1, 7, 28, and 56 days.

The 1- and 7-day iso-strength 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; 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 appears, generally, after 7 days of curing.

Figure 1 indicates also 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-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.

Cost analysis

Figure 2 presents the iso-cost contour lines of the Sundance fly ash concrete mixtures superimposed to the iso-strength contour lines of these concrete mixtures at 1-, 7-, 28-, and 56- days. The prices used in the present study were \$130/tonne for cement and \$65/tonne for fly ash, all in Canadian dollars. The price of the materials will change depending on the location, and therefore, the following observations should not be generalized.

Figure 2 shows that the slope of the iso-cost contour lines was lower than that of the iso-strength lines at 1-day, but higher than that of the iso-strength lines at 7, 28, and 56 days. Therefore, the less expensive concrete mixture proportions that satisfy a criterion related to 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; while, 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 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 \$14 (or ~30%) less than the control concrete, but it developed a 1-day compressive strength of only 5.9 MPa.

The fly ash concrete that developed similar 1-day compressive strength as that of the control concrete was that made with 400 kg of cementitious materials 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 \$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 (Balaine 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.

Point-Tupper fly ash

Figure 3 presents the iso-strength 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.

Figure 3 shows also 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-day. 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 cementitious materials, or underestimate the fly ash content.

Cost analysis

Figure 4 presents the iso-cost contour lines of the Point-Tupper fly ash concrete mixtures superimposed to the iso-strength contour lines of these concrete mixtures at 1, 7, 28, and 56 days. Figure 4 shows that the slope of the iso-cost contour lines was lower than that of the iso-strength lines at 1 and 7 days, and at 28 days for compressive strength below 40 MPa. Therefore, the less expensive concrete mixture proportions that satisfies a criterion related to 1, 7, and 28 days 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 1-day compressive strength of 10 MPa, and 28-day compressive strength similar to that of the control concrete was that made with 350 kg of cementitious materials and incorporating 40% of fly ash. The cost of the fly ash concrete was approximately \$6 (or ~14%) less than 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, that develops adequate 1, and 28-day compressive strengths. The fly ash concrete would still be less expensive than conventional portland-cement concrete with a 28-day compressive strength of 40 MPa.

Conclusion

The above investigation shows that it is possible to proportion a non-superplasticized fly ash concrete with a total cementitious materials 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.

For the Sundance fly ash, it is possible to substitute a non air-entrained conventional portland-cement concrete with a 1-day compressive strength of ~20 MPa with a fly ash concrete incorporating 30% of fly ash, and having similar 1-day strength and similar cost. Such fly ash concrete would, however, develop 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 cementitious materials 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 superplasticizer to enhance the early-age compressive strength of the fly ash concrete, thus leading to the CANMET high-volume fly ash 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 similar 28-day compressive strength fly ash concrete made with 350 kg of cementitious materials 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.

Part II: Effect of a superplasticizer on fly ash concrete

It was concluded in Part I that the potential savings on materials costs due to the use of large proportions of fly ash in the concrete could be used for the addition of a superplasticizer to enhance the early-age compressive strength of the fly ash concrete (by reducing the W/CM). An other way to enhance the early age compressive strength of the fly ash concrete is to reduce the fly ash content in the concrete mixture. The question as to which of the above two solutions would be more economic to achieve a certain 1-day compressive strength will be investigated in this Part. It should be noted, however, that the former concrete would likely be more durable than the later one due to higher fly ash content and lower W/CM that usually increases the impermeability of the concrete.

Scope

Six additional concrete mixtures (i.e. mixture 18 to 23) were made. These included three concrete mixtures with CM content of 300 kg/m^3 incorporating 50% of Sundance fly ash, and made with three dosages of 1, 2, and 3 L/m^3 of a superplasticizer; two concrete mixtures with CM content of 350 kg/m^3 incorporating 40% of Sundance fly ash, and made with two dosages of 1, and 2 L/m^3 of a superplasticizer; one concrete mixtures with CM content of 400 kg/m^3 incorporating 50% of Sundance fly ash, and made with one 1 L/m^3 of a superplasticizer. The water content in the mixture was adjusted to produce a concrete with a slump of 100 ± 20 mm. All concrete mixtures included a water-reducing admixture, and were not air-entrained. For each mixture, the compressive strength was determined on three cylinders at 1, 7, 28, and 56 days.

Materials

The same cement, fly ash (Sundance), admixtures, and the aggregates used in Part I of the present study were also used in Part II. A sodium salt of naphthalene sulfonate polymer was used as a superplasticizer.

Mixture Proportions

The proportions of the concrete mixtures are given in Table 6.

Preparation, Casting, and testing of the Specimens

The procedures for the preparation, casting, and testing of the concrete were the same as those described in the first part of the present paper. Twelve 100 x 200 mm cylinders were cast from each mixture. The cylinders were used for the determination of the compressive strength at 1, 7, 28, and 56 days following the ASTM standard.

Results and Discussion

Properties of fresh concrete

The properties of the fresh concrete are presented in Table 7. The results show that for a slump of approximately 100 mm, the addition of the superplasticizer resulted in decrease of the W/CM, but an increase in the air content of the concrete mixtures. For example, for the concrete mixtures made with 300 kg of total weight of CM, the increase in the dosage of the superplasticizer from 0 to 3 L/m^3 decreased the W/CM from 0.46 to 0.33, but resulted in an increase in the entrapped air content of the concrete from 1.3 to 3.1%.

Compressive strength

The results of the compressive strength of the concrete mixtures are given in Table 8. The addition of the superplasticizer contributed in increasing the compressive strength of the concrete at all ages due to decreased W/CM. For example, for the concrete mixture with a CM content of 300 kg/m^3, the addition of 1, 2, and 3 L/m^3 of the superplasticizer and hence the decrease in the W/CM increased the 1-day compressive strength by 27, 52, and 59%, respectively.

Statistical analysis

Figures 5 and 6 present the iso-strength contour lines of the concrete made with a CM content of 300, and 400 kg/m^3, respectively.

The results show the various combinations of the fly ash content and the dosage of the superplasticizer required for a concrete mixture to achieve a certain compressive strength. For example, for concrete mixtures made with a CM content of 300 kg/m^3 (Fig. 5) to achieve 1-day compressive strength of ~10 MPa, the combinations of fly ash content and SP dosage would range from 40% fly ash with 2.25 L of superplasticizer to 46% fly ash with 3 L of superplasticizer.

Cost analysis

Figures 7 and 8 present the iso-cost contour lines superimposed to the iso-strength contour lines of the superplasticized concrete made with a CM content of 300, and 400 kg/m^3, respectively. The results show that for low content of CM (300 kg/m^3) and for similar 1-day compressive strengths, the concrete mixtures made with higher fly ash content and higher SP dosage cost more than those with lower fly ash content and lower SP dosage. However, Fig.7 shows that for similar 7-, 28-, and 56-days the trend was reversed. Figure 8 shows that for high content of CM (400 kg/m^3) and for similar 1-day compressive strength, the concrete mixtures made with higher fly ash content and higher dosage of the SP cost less than those made with lower fly ash content and lower dosage of the SP.

In order to enhance the early-age compressive strength of concrete with a CM content of approximately 400 kg/m^3, it is more economic to reduce the W/CM by adding a SP and keeping the same fly ash content than to reduce the fly ash content in the concrete mixtures. This, however, is not true for concrete mixtures with a low CM content (~300 kg/m^3).

Part III Effect of air-entraining admixtures (AEA) on fly ash concrete

It is generally recognized that for moderate strength portland-cement concrete, each percent of entrained air reduces the compressive strength by about 5%. The percentage of strength reduction is affected by the cement content, the type of cementitious materials, admixtures, and other concrete ingredients (21-23). In this part of the study, the effect of the air entrainment on the compressive strength of the fly ash concrete was investigated. The figures of the iso-strength given in Part I of the present study can then, be adjusted for concrete incorporating entrained air.

Scope

Seven additional concrete mixtures were made in this part of the study. These included four air-entrained fly ash concrete mixtures, one air-entrained control concrete with a W/C of 0.50, and two additional control concrete with a W/C of 0.45 (with and without AEA). The control concrete (W/CM = 0.45) was added to represent concrete designed for durability. The air-entrained fly ash concrete included two Sundance fly ash concrete mixtures with a CM content of 400 kg/m^3 and fly ash contents of 30 and 50%, and two Point-Tupper fly ash concrete mixtures with CM contents of 300 and 400 kg/m^3 and fly ash content of 30%. The water content of the concrete mixture was adjusted to produce concrete with a slump of 100 ± 20 mm. All concrete mixtures included a water-reducing admixture. For each mixture, the compressive strength was determined on three cylinders each tested at 1, and 7 days, and on two cylinders each tested at 28, and 56 days. Sections cut from two of the cylinders were used to determine the resistance of the concrete to the chloride-ion penetration at 56 days.

Materials

The cement, fly ash, chemical admixtures, and the aggregates used in Part I of the present study were used in Part II as well. A synthetic resin type air-entraining admixture was used.

Mixture Proportions

The proportions of the concrete mixtures are summarised in Table 9.

Preparation, Casting, and testing of the Specimens

The procedure for the preparation, casting, and testing of the concrete were the same as those described in the first part of the present paper. Twelve 100 x 200 mm cylinders were cast from each mixture. The cylinders were used for the determination of the compressive strength at 1, 7, 28, and 56 days, and for the determination of the resistance of the concrete to the chloride-ion penetration at 56 days following ASTM C 39, and C 1012, respectively.

Results and Discussion

Properties of fresh concrete

The properties of the fresh concrete are presented in Table 10. In general, for a given water-to-cementitious materials ratio, the incorporation of the air-entraining admixture contributed to an increase in slump of the concrete.

The dosage of the air-entraining admixture required for obtaining an air content of 5 to 8% ranged from 49 to 56 mL/m^3 for the controls, and from 51 to 203 mL/m^3 for the fly ash concrete. The dosage of the AEA increased with increasing fineness and the fly ash content, and the cementitious materials content.

Compressive strength

The results on the compressive strength of the concrete are given in Table 11. As expected, the use of air-entraining admixture resulted in decreased compressive strength of the concrete at all ages. For the control concrete with a W/C of 0.50 (330 kg of cement), each percent of entrained air reduced the 28-day compressive strength by about 2.6%, and for the control concrete with W/C of 0.45 (370 kg of cement), the reduction of the 28-day compressive strength was about 5.4%. This shows that the reduction in the compressive strength due to entrained air was more severe for control concrete with higher cement content and lower W/C. For the fly ash concrete, the reduction of the 28-day compressive strength due to the entrained air ranged from 4.0 to 5.0%. The type of fly ash, the fly ash content, and the cementitious materials content did not seem to affect the reduction in the compressive strength due to the entrained air significantly.

Statistical analysis

Figures 9 and 10 show the results presented in Part I, and adjusted for a concrete incorporating 6% of air (a reduction of 4.5% in the compressive strength for each percent of entrained air was used at all ages). Figure 9 shows that for an air-entrained Sundance concrete to achieve a 1-day compressive strength of 10 MPa, the combinations of CM and fly ash contents should range linearly from 325 kg/m^3 CM with 30% fly ash to 400 kg/m^3 CM with 47% fly ash. Whereas, for non-air entrained Sundance concrete, Fig. 1 shows that 300 kg/m^3 CM with 35% fly ash to 365 kg/m^3 CM with 50% fly ash should achieve the same 1- day strength.

For Point-Tupper fly ash, Figure 11 shows that none of the combinations of CM and fly ash contents in the ranges investigated were able to yield a concrete mixture with a 1-day compressive strength of 10 MPa.

The results show that with Sundance fly ash, it is possible to proportion less expensive concrete mixtures incorporating up to 50% of fly ash to have adequate 1-day compressive strength (~9 MPa) and 28-day compressive strength similar and even higher than that obtained for both control concrete. With Point-Tupper fly ash and within the range of CM used in this study (i.e. 300 to 400 kg/m^3), the concrete mixtures (made without a superplasticizer) should not incorporate more than 35% fly ash to achieve the above performance.

Chloride-ion penetrability

Table 12 presents the data for the 56-day chloride-ion penetrability for the concrete mixtures tested in this part of the study. The results show that the fly ash concrete largely outperformed the control concrete. The control concrete proportioned for durability (Mix. 26) gave a coulomb value of 3250 that is considered to be of moderate penetrability according to ASTM 1202. Whereas, the concrete incorporating 30 to 50% of Point-Tupper fly ash gave coulombs values ranging from 1630 to 2180 (considered a low chloride-ion penetrability), and those incorporating 30 to 50% Sundance fly ash gave coulombs values ranging from 610 to 770 (considered as a very low chloride-ion penetrability). This is mainly due to the fact that the incorporation of the fly ash in concrete results in finer pores in the hydrated cement paste. This effect is much more so with fine Sundance fly ash due to its high pozzolanicity.

The results show that the increase of the fly ash content from 30 to 50% did not affect significantly the 56-day chloride-ion penetrability of the concrete. However, the results, also show that the control concrete (0% fly ash) could not achieve the performance of the fly ash concrete without increased cost (due to the low W/C, high cement factor and the need for a superplasticizer). Thus, for concrete proportioned for durability, the use of supplementary cementitious materials such as fly ash allows to reduce cost and to produce durable concrete.

Conclusions

It should be noted that the data given in this report are only valid with the type of material and the aggregate grading used in this study. A well planned trial mixtures program using local materials is essential to achieve desired properties when using fly ash.

Non air-entrained concrete made without SP

- For the Sundance fly ash, it is possible to substitute normal portland-cement concrete with w/c of 0.50 and a 28-day compressive strength of 40 MPa with concrete incorporating 50% of fly ash with 1-day compressive strength of 10 MPa and similar 28-day compressive strength at a cost that is 17% less than that of the control concrete. In addition, such concrete would develop significantly higher compressive strength at later ages than the control concrete.
- For the Point-Tupper fly ash, it is possible to substitute the above normal portland-cement concrete with concrete incorporating 40% of fly ash with 1-day compressive strength of 10 MPa and similar 28-day compressive strength at a cost that is 13% less than that of the control concrete. Such concrete would also develop significantly higher long-term compressive strength than the control concrete.

Effect of superplasticizer (SP)

- In order to enhance the early-age compressive strength of the concrete, it was economical to reduce the W/CM by adding a SP than to reduce the fly ash content in the concrete mixtures with a CM content of approximately 400 kg/m^3 and a fly ash content ranging from 30 to 50%. This, however, was not true for concrete mixtures with low CM content (~300 kg/m^3).

Effect of air entrainment

- For fly ash concrete, each percent of entrained air reduces the compressive strength by about 4 to 5%.
- For Sundance fly ash, it is possible to substitute normal air-entrained concrete with a w/c of 0.45 and a 28-day compressive strength of ~40 MPa. with more economical concrete (price reduction of 18% per m^3) incorporating 50% of fly ash with 1-day compressive strength of ~10 MPa and similar 28-day. The fly ash concrete will have very low penetrability to chloride-ion penetration

compared to the moderate penetrability of the control concrete, and much higher later-age compressive strength than the control concrete.

- For the Point-Tupper fly ash, it is possible to substitute the above normal air-entrained concrete with concrete incorporating 30% of fly ash with 1-day compressive strength of ~9 MPa, similar 28-day compressive strength and still reduce the cost by 10%. This fly ash concrete will have low penetrability to chloride-ion compared to the moderate penetrability of the control concrete, and much higher later-age compressive strength than the control concrete.

The conclusions related to the cost of concrete are valid for prices of $130/tonne of cement, $65/tonne of fly ash, and $3/litre of superplasticizer.

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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 45µm, %	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, volume %	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	-	-

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

Mix. no	W/CM*	Water	Cement	Fly Ash			CM*, kg	Fine Aggregate, kg/m³	Coarse Aggregate, kg/m³	WR**, mL/m³
			kg/m³	Type	%	kg/m³				
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

* Cement + fly ash.
** Water reducer.

Table 4 - Properties of the Fresh Concrete

Mixture no.	W/CM*	Fly Ash Type	Fly Ash %	CM*, kg	Unit Weight, kg/m^3	Slump, mm	Air Content, %
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

* Cement + fly ash.

Table 5 - Compressive Strength of Concrete

Mix. no.	W/CM*	Fly Ash		CM*, kg	Density of Hardened Concrete (1-d) kg/m^3	Compressive Strength, MPa				Cost**, $
		Type	%			1 d	7 d	28 d	56 d	
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

* Cement + fly ash.

** The cost is based on the price of the cementitious materials used, i.e. $130/tonne for cement and $65/tonne for fly ash (all figures are in Canadian Dollars).

Table 6 - Proportions of the Concrete Mixtures (Effect of Superplasticizer)

Mix. no	W/CM*	Water	Cement	Sundance Fly Ash		CM*, kg	Fine Agg., kg/m^3	Coarse Agg., kg/m^3	WR**, mL/m^3	SP***, L/m^3
			kg/m^3	%	kg/m^3					
3	0.46	139	150	50	150	~300	797	1195	526	0
18	0.41	124	151		151		805	1209	528	1
19	0.37	112	151.5		152		809	1215	530	2
20	0.33	101	153		153		818	1228	536	3
6	0.43	154	214	40	143	~350	768	1152	750	0
21	0.39	140	214		143		776	1167	751	1
22	0.35	128	217		145		789	1186	759	2
5	0.38	155	202	50	202	~400	744	1114	706	0
23	0.35	141	201		201		767	1147	703	1

* Cement + fly ash.
** Water reducer.
*** Superplasticizer.

Table 7 - Properties of the Fresh Concrete (Effect of Superplasticizer)

Mixture no.	W/CM*	Sundance Fly Ash, %	CM*, kg	Unit weight, kg/m^3	Slump, mm	Air Content, %
3	0.46	50	~300	2432	90	1.3
18	0.41			2432	90	1.9
19	0.37			2432	100	2.0
20	0.33			2446	170	3.1
6	0.43	40	~350	2432	90	1.6
21	0.39			2418	90	2.0
22	0.35			2432	80	2.6
5	0.38	50	~400	2418	90	1.4
23	0.35			2403	100	1.9

* Cement + fly ash.

Table 8 - Compressive Strength of Concrete (Effect of Superplasticizer)

Mix. no.	W/CM*	Sundance Fly Ash, %	CM*, kg	SP**, L/m^3	Density of Hardened Concrete (1-d) kg/m^3	Compressive Strength, MPa				Cost***, $
						1 d	7 d	28 d	56 d	
3	0.46	50	~300	0	2435	5.9	21.8	41.8	47.0	29.25
18	0.41			1	2429	7.5	26.2	47.3	54.3	33.25
19	0.37			2	2448	9.0	32.6	54.3	60.6	37.25
20	0.33			3	2437	9.4	35.5	58.4	63.7	41.25
6	0.43	40	~350	0	2410	10.5	29.7	52.7	60.0	36.92
21	0.39			1	2413	12.1	31.7	54.1	59.0	41.12
22	0.35			2	2425	14.6	38.9	58.0	65.0	45.64
5	0.38	50	~400	0	2403	12.3	34.6	55.7	62.0	39.6
23	0.35			1	2403	14.8	38.5	58.2	64.1	43.6

* Cement + fly ash.
** Superplasticizer.
*** The cost is based on the price of the cementitious materials used, i.e. $130/tonne for cement and $65/tonne for fly ash (all figures are in Canadian Dollars).

Table 9 - Proportions of the Concrete Mixtures (Effect of Air Entrainment)

Mix no	W/CM*	Water	Cement	Fly Ash			CM*, kg	Fine Agg., kg/m³	Coar. Agg., kg/m³	AEA**, mL/m³	WR***, mL/m³
			kg/m³	Type	%	kg/m³					
1	0.50	165	331	-	0	0	~330	768	1153	0	1159
24		164	328					718	1080	49	1148
25	0.45	167	370				~370	754	1126	0	1850
26		170	374					705	1056	56	1310
4	0.42	163	273	Sund -ance	30	117	~400	746	1118	0	954
27		166	279			120		672	1010	160	978
5	0.38	155	202		50	202		744	1114	0	706
28		153	203			203		687	1031	203	710
10	0.52	159	213	Point - Tupper	30	91	~300	781	1172	0	745
29		158	211			90		732	1098	51	739
12	0.44	174	274		30	117	~400	742	1109	0	960
30		173	272			116		692	1036	86	952

* Cement + fly ash.
** Air entraining admixture.
*** Water reducer.

Table 10 - Properties of the Fresh Concrete (Effect of Air Entrainment)

Mixture no.	W/CM*	Fly Ash		CM*, kg	Unit Weight, kg/m^3	Slump, mm	Air Content, %
		Type	%				
1	0.50	-	0	~330	2418	100	2.0
24					2290	140	7.4
25	0.45			~370	2418	75	2.4
26					2305	170	6.6
4	0.42	Sundance	30	~400	2418	90	1.6
27					2248	160	8.0
5	0.38		50		2418	90	1.4
28					2280	170	5.8
10	0.52	Point -Tupper	30	~300	2418	110	1.7
29					2290	160	7.5
12	0.44			~400	2418	120	1.5
30					2290	180	6.5

* Cement + fly ash.

Table 11 - Compressive Strength of Concrete (Effect of Air Entrainment)

Mix. no.	W/CM*	Fly Ash		CM*, kg	Air Content, %	Density of Hardened Concrete (1-d), kg/m^3	Compressive strength, MPa				Cost**, $	R(28d)***, %
		Type	%				1 d	7 d	28 d	56 d		
1	0.50	-	0	~330	2.0	2420	19.4	32.6	40.1	43.0	42.9	2.6
24					7.4	2310	17.4	27.5	34.5	37.0	42.6	-
25	0.45			~370	2.4	2434	27.6	40.0	49.5	53.2	48.1	5.4
26					6.6	2315	21.9	31.5	38.3	41.2	48.6	-
4	0.42	Sund -ance	30	~400	1.6	2286	18.5	36.5	56.0	61.0	44.9	4.2
27					8.0	2242	13.9	25.9	41.1	45.2	44.1	-
5	0.38		50		1.4	2410	12.3	34.6	55.7	62.0	40.0	5.0
28					5.8	2290	9.8	27.4	43.5	51.3	39.6	-
10	0.50	Point -Tupper	30	~300	1.7	2440	7.2	22.5	35.9	41.0	33.2	4.9
29					7.5	2310	5.0	17.4	25.7	31.5	32.8	-
12	0.41			~400	1.5	2430	11.7	31.5	44.6	50.0	43.7	4.0
30					6.5	2300	9.5	24.2	35.6	40.6	43.4	-

* Cement + fly ash,

** The cost is based on the price of the cementitious materials used, i.e. $130/tonne for cement and $65/tonne for fly ash (all figures are in Canadian Dollars).

*** The reduction in 28-day compressive strength corresponded to one percent increase in the air content, and calculated as follows:
R(28d)% = [(f=c(non-air) - f=c(air))/(f=c(non-air)) * 100]/[A%(air) - A%(non air)]

Table 12 - Chloride-Ion Penetrability of Concrete

Mix. no.	W/CM*	Fly Ash		CM*, kg	Air Content, %	Chloride-Ion Penetrability at 56 days, Coulombs
		Type	%			
1	0.50	-	0	~330	2.0	3820
24					7.4	4120
25	0.45			~370	2.4	3630
26					6.6	3250
4	0.42	Sund -ance	30	~400	1.6	550
27					8.0	770
5	0.38		50		1.4	620
28					5.8	610
10	0.52	Point - Tupper	30	~300	1.7	2140
29					7.5	2180
12	0.44			~400	1.5	1750
30					6.5	1630

* Cement + fly ash.

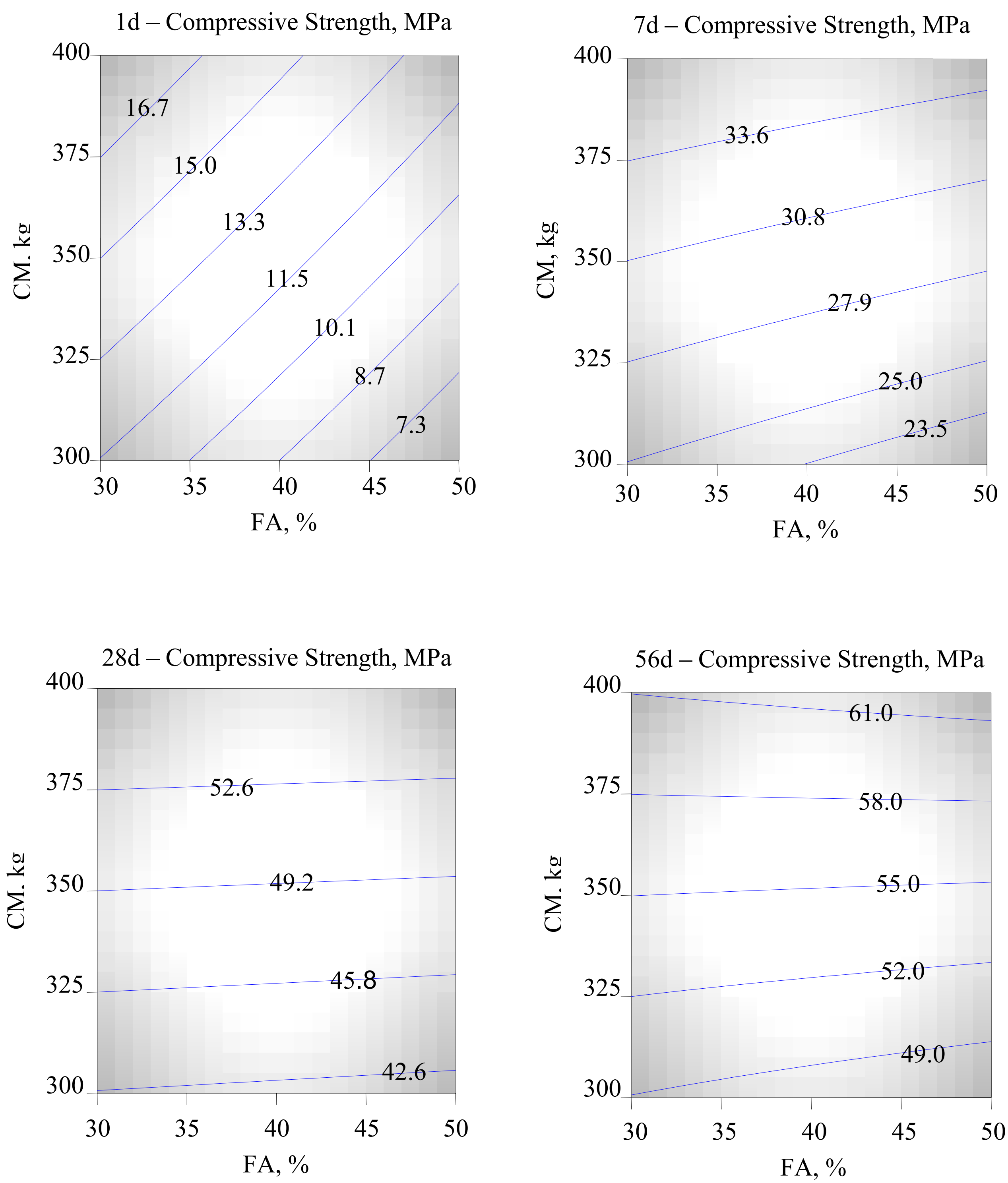

Fig. 1: Iso-strength lines of Sundance fly ash concrete.

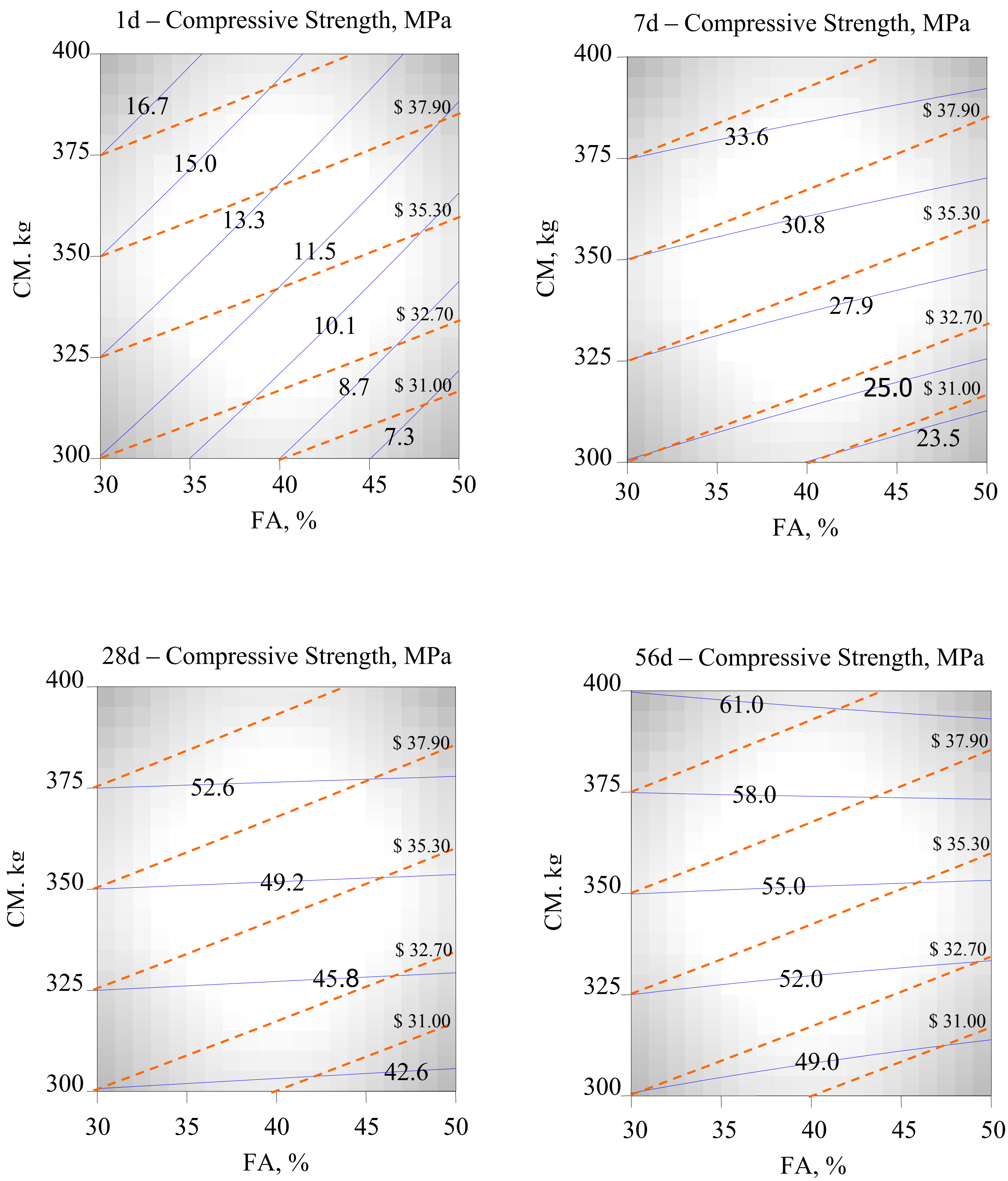

Fig. 2: Iso-cost lines superimposed to iso-strength lines of Sundance fly ash concrete. The solid line corresponds to compressive strength; the dashed line corresponds to the cost, in Canadian dollars.

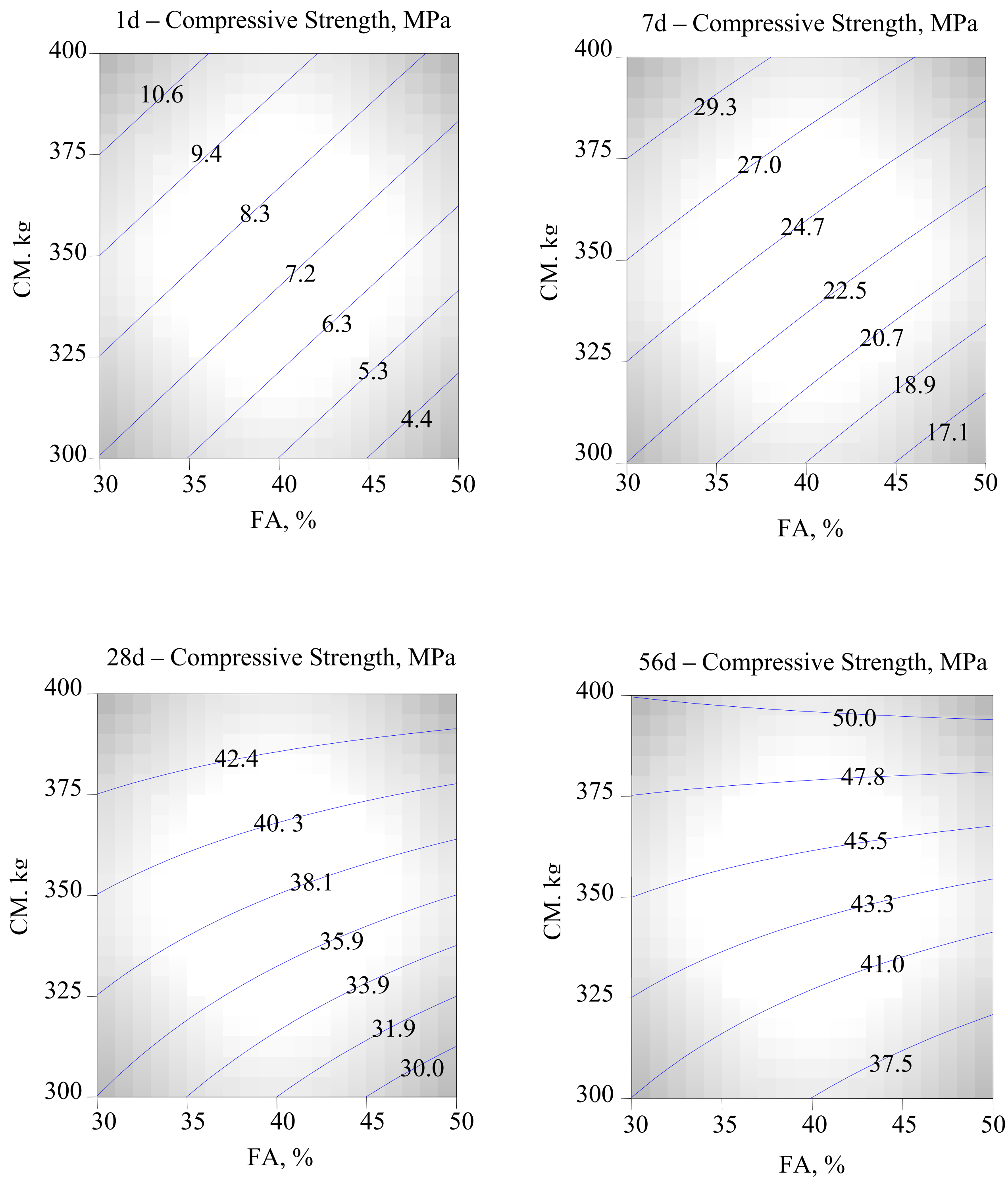

Fig. 3: Iso-strength lines of Point Tupper fly ash concrete.

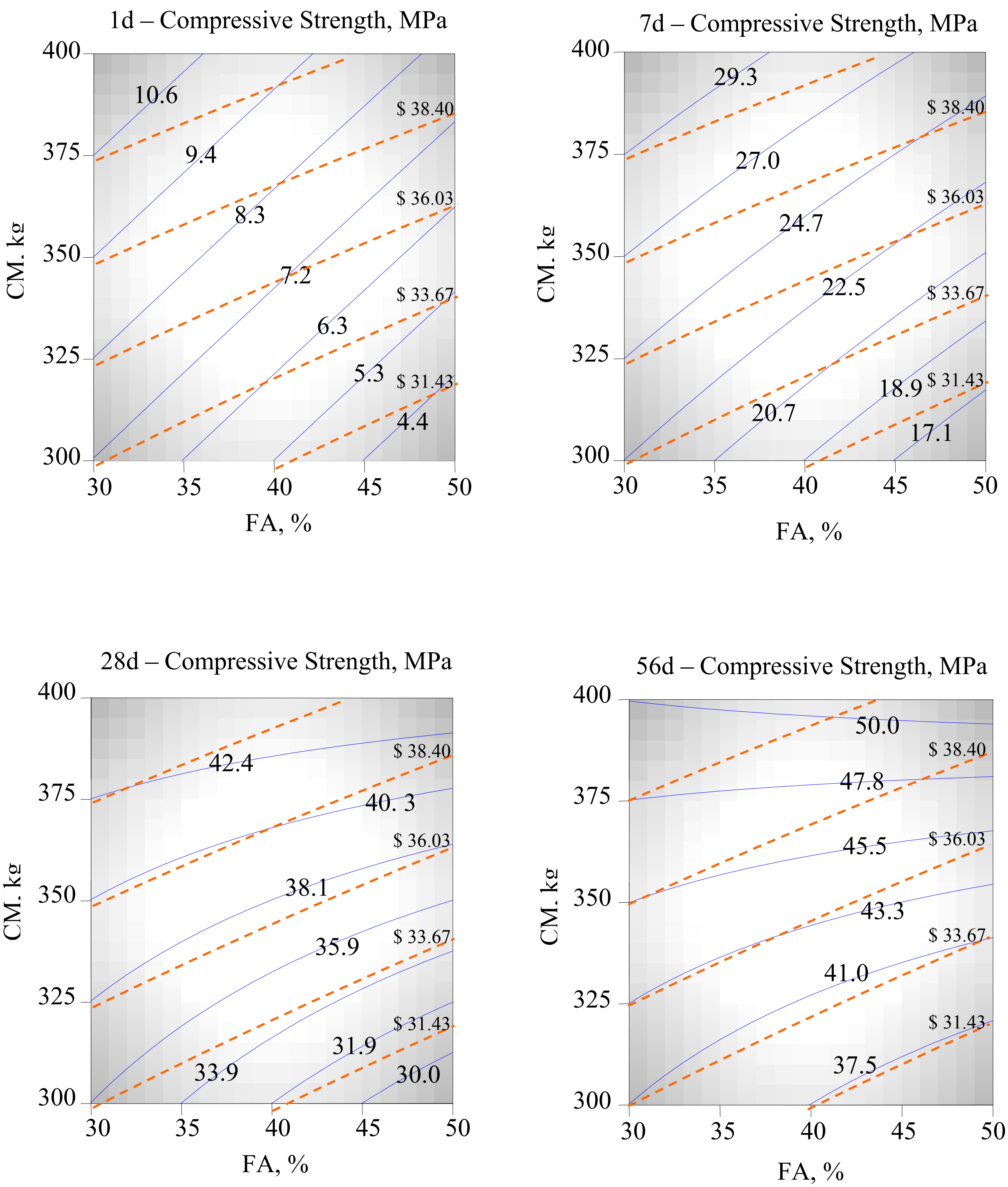

Fig. 4: Iso-cost lines superimposed to iso-strength lines of Point-Tupper fly ash concrete. The solid line corresponds to compressive strength; the dashed line corresponds to the cost, in Canadian dollars.

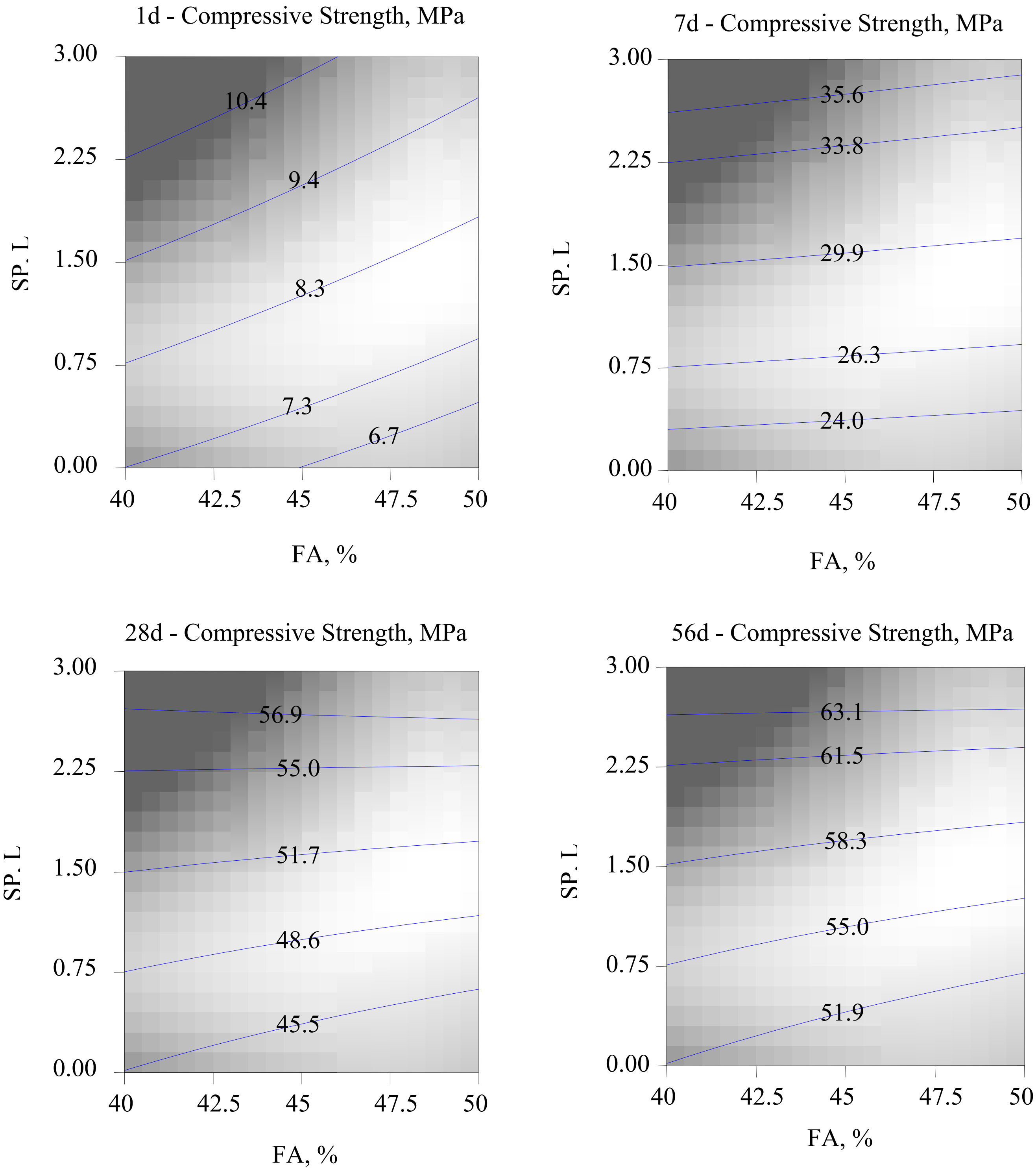

Fig. 5: Iso-strength lines of superplasticized concrete with a cementitious materials content of 300 kg/m^3

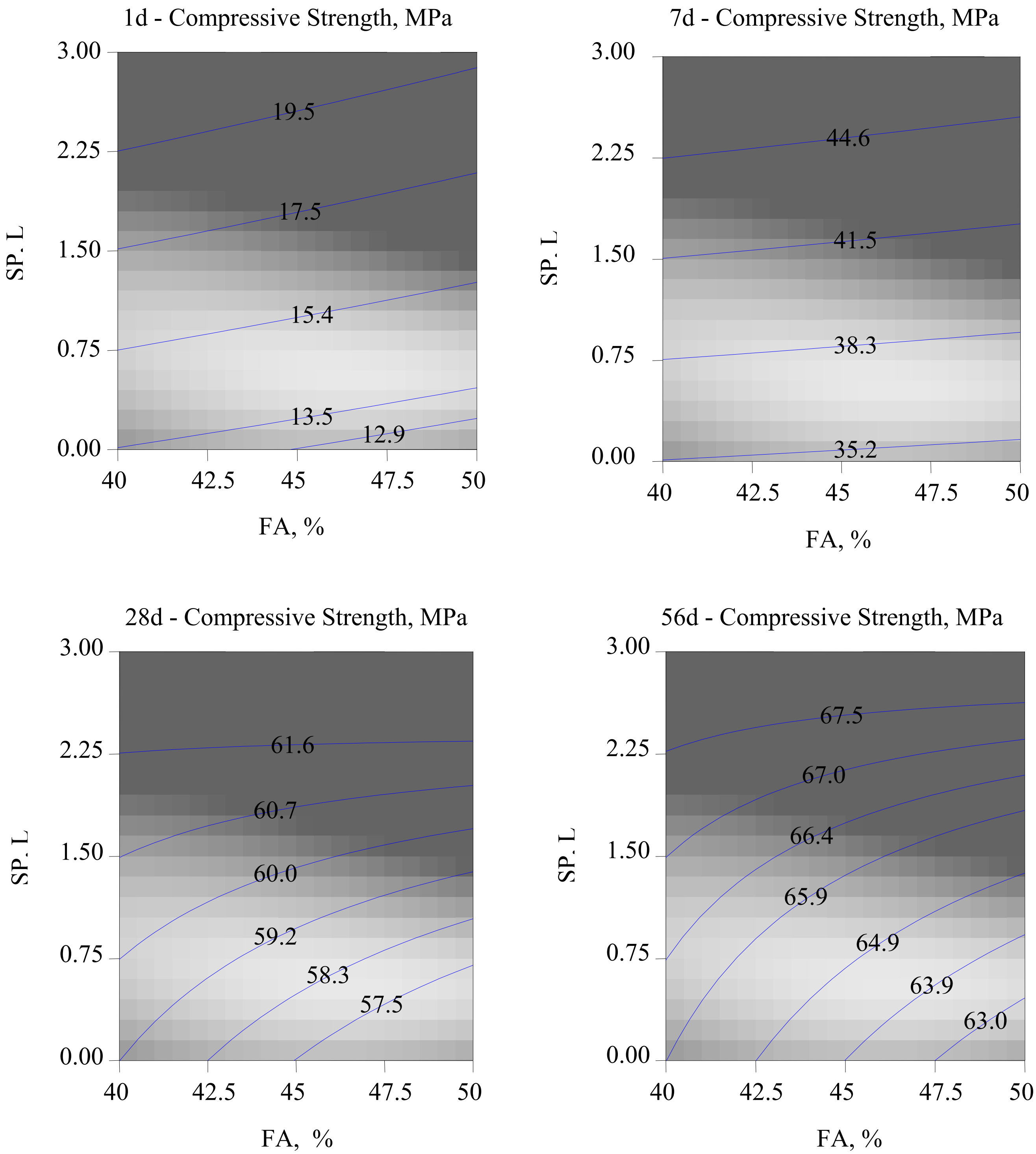

Fig. 6: Iso-strength lines of superplasticized concrete with a cementitious materials content of 400 kg/m^3

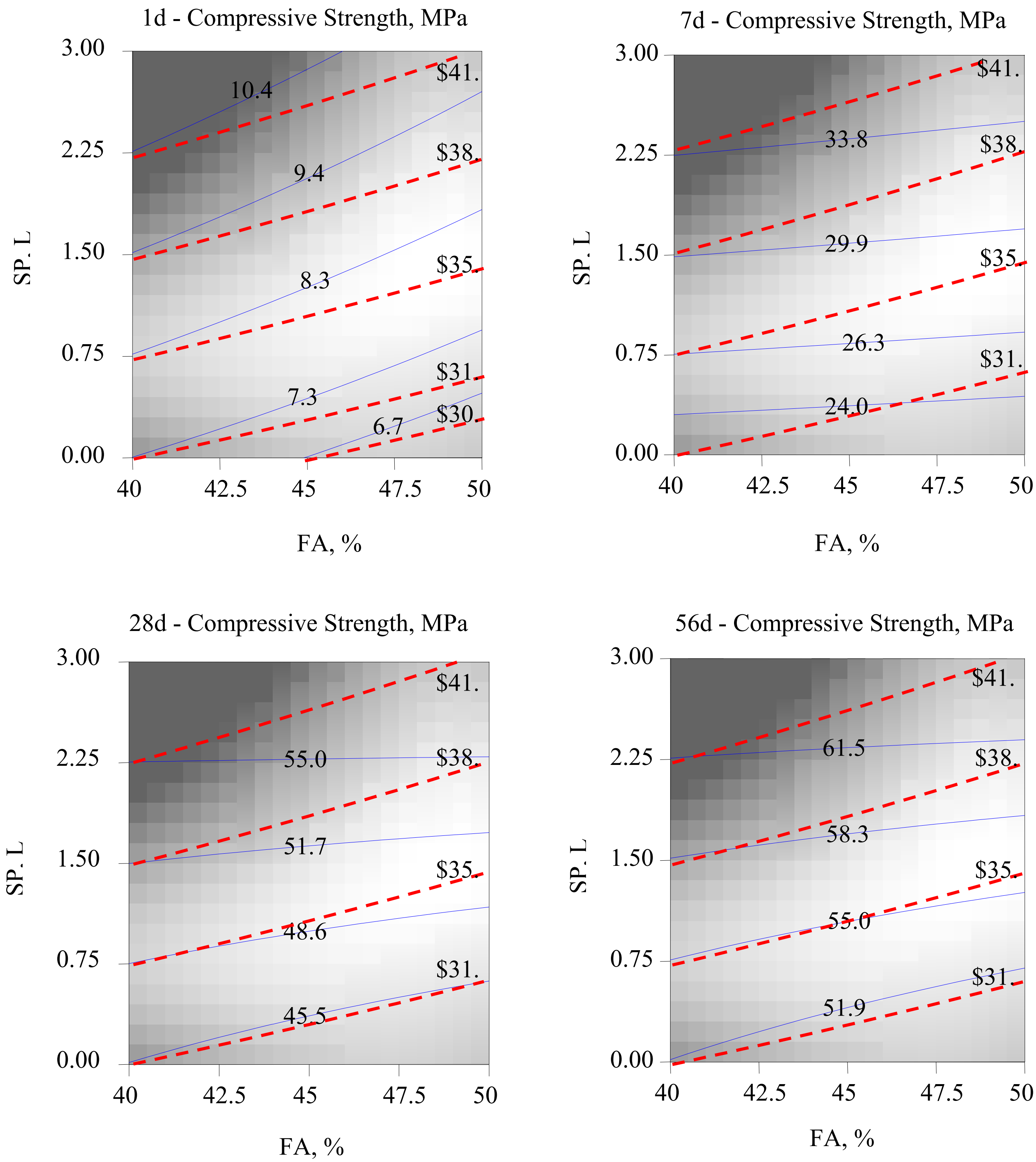

Fig. 7: Iso cost lines superimposed to Iso-strength lines of superplasticized concrete with a cementitious materials content of 300 kg/m^3. The solid line corresponds to compressive strength; the dashed line corresponds to the cost, in Canadian dollars.

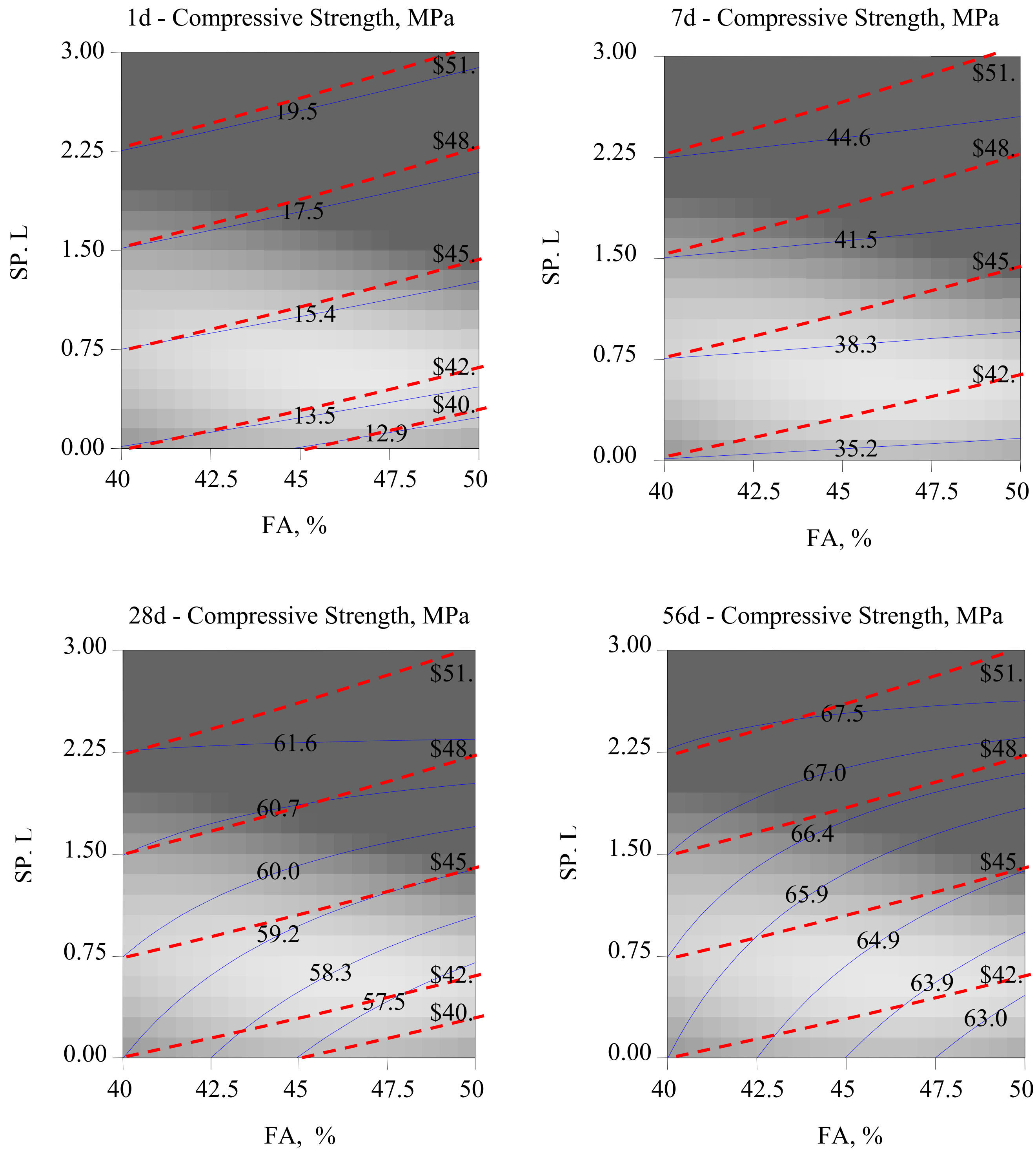

Fig. 8: Iso cost lines superimposed to Iso-strength lines of superplasticized concrete with a cementitious materials content of 400 kg/m^3. The solid line corresponds to compressive strength; the dashed line corresponds to the cost, in Canadian dollars.

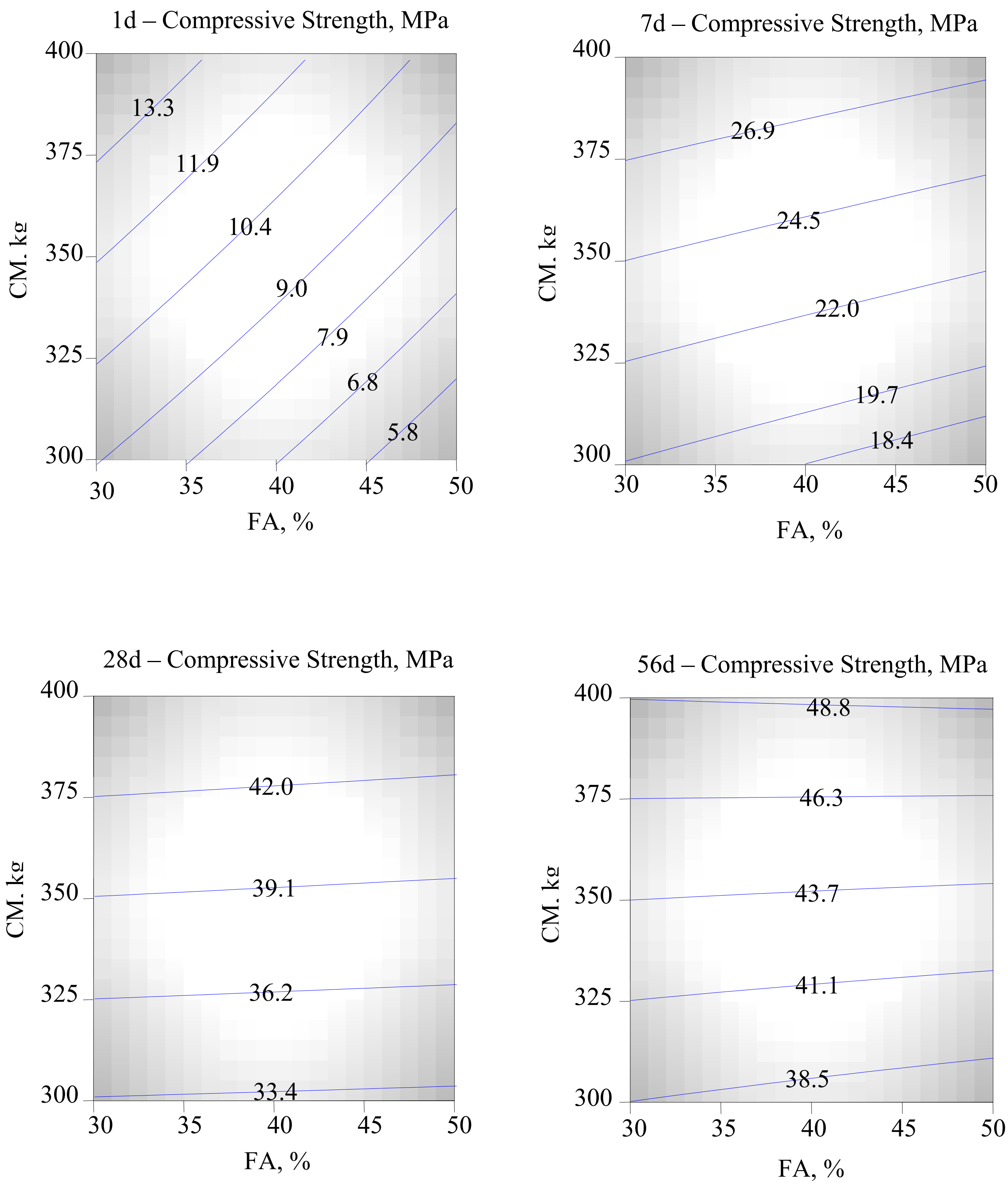

Fig. 9: Iso-strength lines of air-entrained Sundance fly ash concrete.

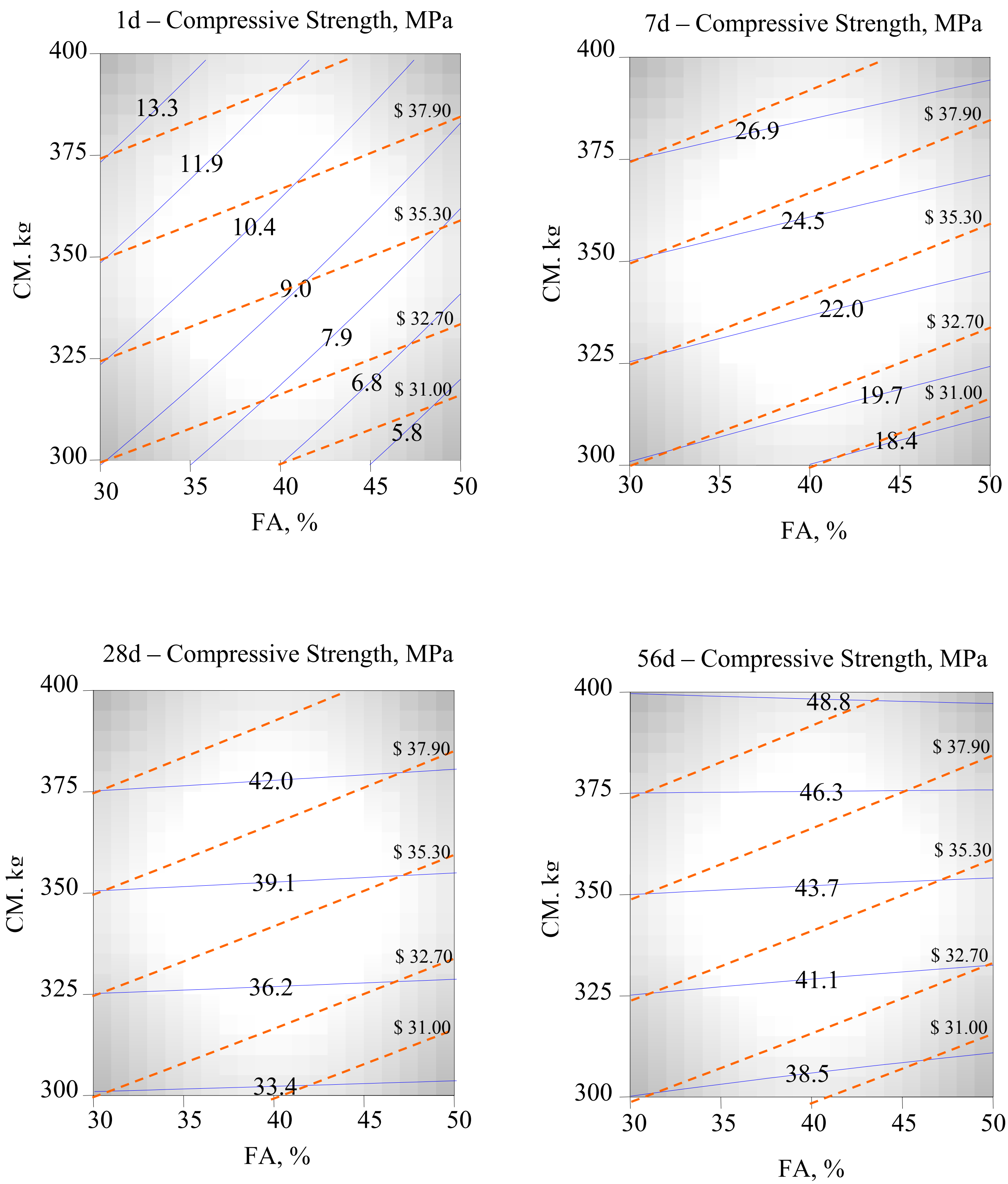

Fig. 10: Iso-cost lines superimposed to iso-strength lines of air-entrained Sundance fly ash concrete. The solid line corresponds to compressive strength; the dashed line corresponds to the cost, in Canadian dollars.

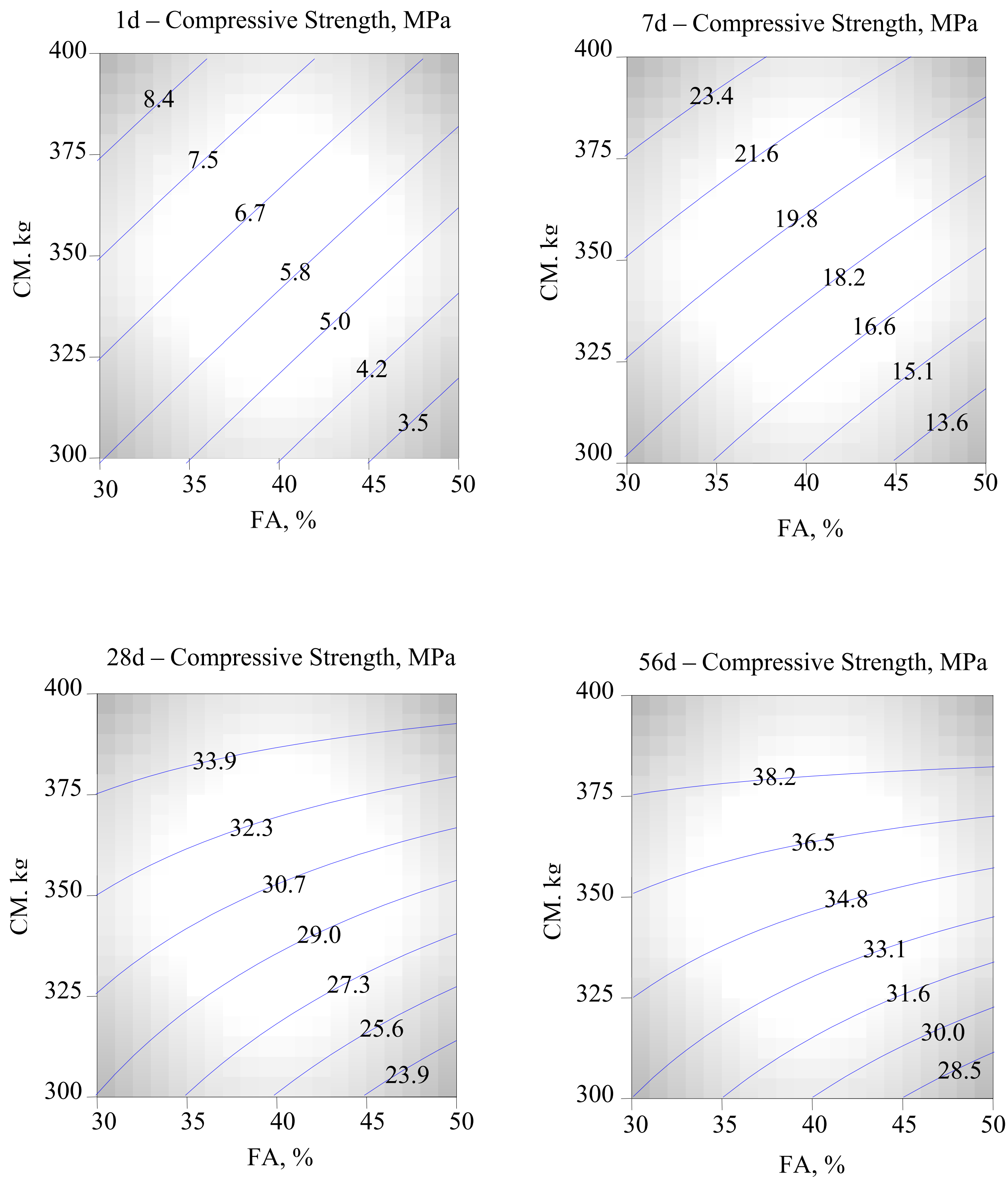

Fig. 11: Iso-strength lines of air-entrained Point Tupper fly ash concrete.

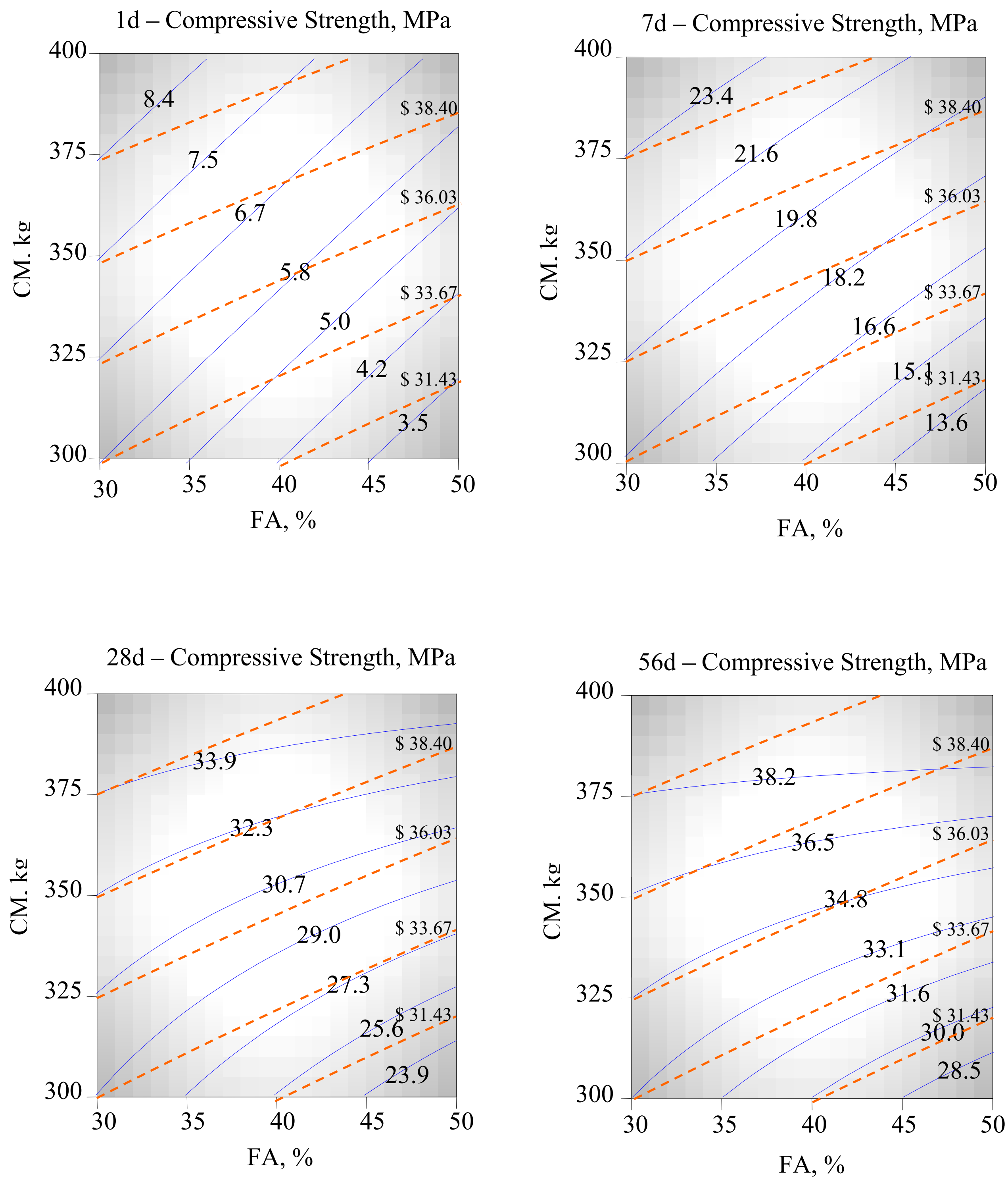

Fig. 12: Iso-cost lines superimposed to iso-strength lines of air-entrained Point-Tupper fly ash concrete. The solid line corresponds to compressive strength; the dashed line corresponds to the cost, in Canadian dollars.