MATERIALS TECHNOLOGY LABORATORY

Effect of Low-curing Temperatures
on Selected Properties of Concrete Incorporating
Large Volumes of Fly Ash

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EFFECT OF LOW-CURING TEMPERATURES ON SELECTED PROPERTIES OF CONCRETE INCORPORATING LARGE VOLUMES OF FLY ASH

by

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ABSTRACT

The main objective of this project was to observe the effect of low-curing temperatures on the setting time, strength development and resistance to chloride-ion penetration of concrete incorporating large volumes of fly ash. The internal temperature of various size specimens was also monitored. The cement replacement levels by fly ash were 30, 40 and 50 percent, and the fly ash concrete along with the control concrete were exposed to ambient temperatures of 5, 14 and 22 degrees Celsius.

In this study, the cement used was a CSA Type 10 normal portland cement and the fly ash was a CSA Class CI (ASTM Class F) fly ash from Western Canada. The concrete mixtures were designed to produce 28-day compressive strengths of 40 MPa, with a slump of approximately 100 mm and an air content in the range of 6.0 to 6.5 percent. The cementitious content ranged from 340 kgim3 with a water-to-cement ratio of 0.45 for the control concrete, to 400 kgim3 with a water-to- cementitious ratio of 0.36 for the fly ash concrete at the 50 percent replacement level. All concrete mixtures were air entrained and contained a water-reducing admixture.

The properties of both the control concrete and the fly ash concretes are adversely affected by lower curing temperatures. The longer-setting time of the fly ash concrete compared with the control concrete is amplified at lower temperatures. Although the compressive strength of all fly ash concretes is comparable after 56 days regardless of curing temperatures or fly ash replacement levels, the early age strength development of the fly ash concrete is somewhat more affected by lower curing temperatures than the control concrete. As for chloride permeability, it appears that lower curing temperatures have little or no effect on the resistance to chloride-ion penetration at 56 days of either the control or the fly ash concrete.

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INTRODUCTION

The main objective of this project was to observe the effect of low curing temperatures on the setting time, strength development and resistance to chloride-ion penetration of concrete incorporating large volumes of CSA Class CI (ASTM Class F) fly ash. The internal temperatures of various size specimens was also monitored.

SCOPE

In this investigation four concrete mixtures were made. These included one control concrete mixture and three fly ash concrete mixtures. The cement replacement levels by fly ash were 30, 40 and 50 percent, and the fly ash concrete along with the control concrete were exposed to ambient temperatures of 5, 14 and 22 degrees Celsius. Both the control and fly ash concrete mixtures were designed to produce 28-day compressive strengths of 40 MPa, with a slump of approximately 100 mm and an air content in the range of 6.0 to 6.5 percent. The cementitious content ranged from 340 kgim3 with a water-to-cement ratio of 0.45 for the control concrete, to 400 kg/m3 with a water to cement ratio of 0.36 for the fly ash concrete at the 50 percent replacement level. All concrete mixtures were air entrained and contained a water-reducing admixture. Triplicate concrete batches were made, for the control concrete and each of the three replacement levels of the fly ash concrete. The batches were made in triplicate in order to have one batch for each of the three ambient temperatures. From each batches, a number of specimens were cast to determine the strength development of the concretes at various ages up to 56 days. At 56 days cores were extracted from large cylinders for chloride-ion penetration testing. All specimens were exposed to the various ambient temperatures immediately after casting and remained in those conditions until testing. The setting time of the concretes exposed to the different ambient temperatures was also determined.

MATERIALS

The cement used for the concrete mixtures was a CSA Type 10 normal portland cement and the fly ash was a CSA Class CI (ASTM Class F) fly ash from Western Canada. The physical properties and the chemical analysis of the cement and the fly ash are given in Table 1. The air- entraining admixture was a synthetic resin type and the water-reducing admixture was composed of modified polymers and lignosulfonates. The fine aggregate used was natural sand and the coarse aggregate was 19-mm maximum size crushed limestone. The grading and properties of both aggregates are given in Tables 2 and 3 respectively.

CONCRETE MIXTURES

The concrete mixtures made included one air-entrained control concrete and three air- entrained fly ash concretes incorporating 30, 40 and 50% replacement by mass of cement by fly ash.

The proportions of the four mixtures are shown in Table 4. The mixtures were designed to produce similar compressive strengths at 28 days ($\pm$ 40 MPa) when cured at normal temperature. This explains the differences in the water-to-cementitious materials ratio (W /(C+F A) which ranges from 0.45 for the control concrete to 0.36 for the concrete with 50% fly ash. Each concrete mixture was prepared in triplicate batches of 91 litres each, and to reduce variability, these were made on the same day. The batches were made in a laboratory counter-current mixer. The properties of the fresh concrete including slump, unit weight and air content are given in Table 5.

CASTING, CURING AND TESTING OF SPECIMENS

From each concrete batch twenty two 102 x 203-mm cylinders were cast for compressive strength testing at 1, 2, 3, 7,28 and 56 days. Provisions were made to have 3 cylinders per test age and 1 extra cylinder to monitor internal temperatures. Along with these cylinders, three 152 x 305- mm cylinders were cast; two for compressive strength testing at 56 days and one for temperature monitoring. Additionally, one 305 x 356-mm cylinder was cast for internal temperature monitoring. This cylinder was later cored in order to have specimens for chloride permeability testing at 56 days. Immediately after casting, the specimens were exposed to the three different temperatures until tested. The specimens were kept in the molds for 7 days with the top surface protected from moisture loss with wet burlap. At 7 days the top surface of the 305 x 356-mm cylinder was exposed to air while the specimen remained in its mold. The remainder of the specimens were removed from their molds, wrapped in wet towels and then covered with a plastic film wrap before returning them to their appropriate curing environments.

TEST RESULTS

Immediately after casting, the temperature of the designated specimens was monitored for 70 hours and the resulting data from the control concrete and a typical fly ash concrete are illustrated in Figs. 1 and 2. The results for setting time can be viewed in Figs. 3 to 6 and a summary of the compressive strength test results is given in Table 6 and the data are illustrated in Figs. 7 to 10. The chloride-ion penetration testing results are shown in Table 7.

DISCUSSION OF TEST RESULTS

Temperature Rise

As expected the temperature of the larger size specimens was less affected by the lower temperatures due to the effect of mass, where the heat-of -hydration is dissipated at a lower rate. This effect is displayed in Fig. 1 with the control concrete at room temperature, where the 305 x 356-mm cylinder reaches peak temperatures close to 40.C compared with 30.C for the 102 x 203-mm cylinder. Both the temperature development of the control concrete and the fly ash concrete is significantly more affected at 5.C than at 14.C (Figs. 1 and 2). It can also be observed that the peak temperatures of the fly ash concrete is delayed compared with the control concrete. This can be explained by the reduced heat-of-hydration normally produced in fly ash concrete. The peak temperature difference at room temperature between the control concrete and the fly ash concrete ranges from 5 to 10.C depending on the size of the specimen.

Setting Time

At 5 degrees Celsius the setting time of the fly ash concrete is considerably affected. At the 50 percent replacement level (Fig. 6) the final setting time of the fly ash concrete is delayed by 17 hours and 45 minutes from that of the fly ash concrete at 22 degrees Celsius. This in comparison with a delay 9 hours and 10 minutes for the control concrete (Fig. 3) exposed to 5 degrees from the one at 22 degrees. At this low temperature, the final setting time for the control concrete was 16 hours and 30 minutes, and 27 hours and 25 minutes for the fly ash concrete at the 50 percent replacement level. At 14 degrees Celsius the effect is less evident with a delay of 4 hours 50 minutes for the same fly ash concrete compared with a delay of 2 hours and 45 minutes for the control concrete. At that temperature we have a final setting time of 10 hours and 5 minutes for the control concrete versus 14 hours and 30 minutes for the fly ash concrete at the 50 percent replacement level. Evidently as the fly ash replacement diminishes (Fig. 4 and 5) the setting time of the fly ash concrete is less affected by the lower temperatures.

Compressive Strength

The early-age compressive strength of the control concrete and the fly ash concrete were adversely affected by lower curing temperatures. Although the effect of the lower temperatures on the compressive strength of the fly ash concrete was still noticeable after 28 days compared with 7 days for the control concrete, at 56 days the compressive strength of the concretes exposed to the lower temperatures was comparable to the ones exposed to room temperature. The fly ash concretes exposed to 5 degrees Celsius showed higher compressive strengths at 56 days than the ones at 14 degrees Celsius. This is true at all three replacement levels (Figs. 8 to 10).

As seen in Table 6, when we compare both the control concrete with the fly ash concrete at the 50 percent replacement level exposed to 5 degrees Celsius, the I-day compressive strengths of the control concrete was 5.9 MPa and that of the fly ash concrete at the 50 percent replacement level was 0.7 MPa. For the same concretes at 3 days the compressive strength were 20.6 MPa and 12.3 MPa respectively, at 7 days the compressive strengths were 30.1 MPa and 21.0 MPa, at 28 days they were 39.3 MPa and 30.0 MPa and finally at 56 days the compressive strength of the control concrete was 41.2 and that of the fly ash concrete at the 50 percent replacement level was 45.2 MPa. It should be noted that the control concrete and the fly ash concrete at all replacement levels reached compressive strengths in excess of 39 MPa at 56 days, regardless of the curing temperature.

Chloride Permeability

In this study, the resistance to chloride-ion penetration of the fly ash concrete improves proportionally with progressively higher quantities of fly ash in the concrete. This is also partly explained by the lower W /(C+F A) of the fly ash concrete. On average the resistance to chloride-ion penetration at 56 days of the fly ash concrete ranged from approximately 1000 coulombs at 30 percent replacement level to 340 coulombs at 50 percent replacement level. This quality does not seem to be affected by lower curing temperatures. For example as shown in Table 7, the resistance to chloride-ion penetration of the fly ash concrete at the 50 percent replacement level exposed to 22'C was 202 coulombs compared with 229 coulombs for the same concrete exposed to 5'C. The control concrete exposed to 22 'C for 56 days was 5116 coulombs compared with 2759 for the control concrete exposed to 5'C. As seen in Table 6, at 14 degrees Celsius, the values for the control concrete and the fly ash concrete at the three replacement levels are somewhat higher than expected. This is probably due to the air circulation system in the environmental chamber used for this particular temperature exposure. The higher air circulation contributed to an increased drying of the exposed surface of the 305 x 356-mrn cylinders where the samples for chloride-ion penetration testing were taken. The increased drying would have affected the reaction process in the concrete near the surface thus increasing it's permeability and consequently reducing its resistance to chloride-ion penetration.

CONCLUSION

The properties of both the control concrete and the fly ash concretes are adversely affected by lower curing temperatures, especially at early ages. However the effect was more significant for the fly ash concrete. The longer-setting time of the fly ash concrete compared with the control concrete is amplified at lower temperatures. This would definitely be a concern for finishing operation of floor slabs made with concrete incorporating large volumes of fly ash placed at lower temperatures. Although the compressive strength of all fly ash concretes is comparable after 56 days regardless of curing temperatures or fly ash replacement levels, the early age strength development of the fly ash concrete is somewhat more affected by lower curing temperatures than the control concrete. Therefore care should be taken to ensure proper strength levels for removal of form work. As for chloride permeability, it appears that, if proper moist curing is provided to the concrete in the first 7 days, the lower curing temperatures have little or no effect on the resistance to chloride-ion penetration at later age of either the control or the fly ash concrete. This investigation explores the effect of low-curing temperatures on a limited number of properties of concrete incorporating large volumes of one fly ash only. Further research is needed in this area.

Table 1 - Physical Properties and Chemical Analysis of Cement and Fly Ash

	CSA Type 10 Cement	CSA Class CI (ASTM Class F) Fly Ash
Physical Properties		
Fineness		
- passing 45μm, %	93.7	83.6
-surface area (Blaine), m^2/kg	408	320
Specific gravity	3.15	2.08
Compressive strength, MPa		
7 days	34.0	-
28 days	41.9	-
Strength Activity Index, %		
7 days	-	95.5
28 days	-	106.9
Chemical Analysis, %		
Silicon dioxide (SiO_2)	20.10	52.40
Aluminum oxide (Al_2O_3)	4.24	23.40
Ferric oxide (Fe_2O_3)	2.90	4.70
Calcium oxide (CaO)	62.70	13.40
Magnesium oxide (MgO)	2.58	1.30
Sulphur trioxide (SO_3)	3.04	0.21
Sodium oxide (Na_2O)	0.26	3.60
Potassium oxide (K_2O)	0.84	0.60
Loss on ignition (LOI)	2.01	0.30

Table 2 - Grading of Aggregates

Coarse Aggregate		Fine Aggregate	
Sieve size, mm	Cumulative % retained	Sieve size, mm	Cumulative % retained
19.0	0	4.75	2.9
12.5	40	2.36	12.4
9.5	65	1.18	23.3
4.75	100	0.6	47.7
		0.3	83.4
		0.15	96.0

Table 3 - Physical Properties of Aggregates

	Coarse Aggregate (Crushed Limestone)	Fine Aggregate (Natural Sand)
Specific Gravity	2.72	2.73
Absorption, %	0.40	0.80

Table 4 - Concrete Mixture Proportions

Mixture Type	Exposure Temperature	$\frac{W}{(C + FA)}$	Batch Quantities, kg/m³					A.E.A.* mL/m³	W.R.A.** mL/m³
			Cement	Fly Ash	Water	Coarse Agg.	Fine Agg.		
Control	5 °C	0.45	340	0	153	1102	735	50	900
	14°C	0.45	343	0	154	1108	740	50	900
	22°C	0.45	340	0	153	1102	735	50	900
30% Fly Ash	5 °C	0.40	254	109	145	1068	712	100	700
	14°C	0.40	256	110	146	1075	716	100	700
	22°C	0.40	257	111	147	1082	721	100	700
40% Fly Ash	5 °C	0.38	233	156	148	1059	707	130	600
	14°C	0.38	234	157	149	1066	711	130	600
	22°C	0.38	236	158	150	1072	715	130	600
50% Fly Ash	5 °C	0.36	206	206	148	1046	697	200	500
	14°C	0.36	202	202	146	1027	684	200	500
	22°C	0.36	204	204	148	1039	693	200	500

* Air entraining admixture
** Water Reducing Admixture

Table 5 - Properties of Fresh Concrete

Mixture Type	Exposed Temperature	Unit Weight kg/m³	Slump mm	Air Content %
Control	5 °C	2330	100	6.8
	14°C	2345	95	6.6
	22°C	2330	100	6.8
30% Fly Ash	5 °C	2290	140	6.8
	14°C	2305	115	6.7
	22°C	2320	130	6.4
40% Fly Ash	5 °C	2305	115	6.2
	14°C	2320	100	6.0
	22°C	2330	100	5.8
50% Fly Ash	5 °C	2305	115	6.0
	14°C	2260	130	6.6
	22°C	2290	110	6.2

Table 6 - Summary of Compressive Strength Test Results

Mixture Type	Exposed Temperature	Compressive Strength, MPa (cylinder size)						
		(102 x 203-mm)*						(152 x 305-mm)**
		1 day	2 days	3 days	7 days	28 days	56 days	56 days
Control	5 °C	5.9	14.8	20.6	30.1	39.3	41.2	41.1
	14°C	17.9	23.5	26.7	32.8	39.4	43.8	41.0
	22°C	22.5	26.3	28.1	32.5	39.5	41.0	40.4
30% Fly Ash	5 °C	1.4	6.8	13.1	23.1	34.6	43.4	42.2
	14°C	9.0	16.9	20.1	26.4	36.4	40.8	42.9
	22°C	14.4	19.9	23.3	28.9	40.1	43.8	47.3
40% Fly Ash	5 °C	1.6	8.1	14.7	23.1	33.6	46.3	45.2
	14°C	8.2	16.9	21.7	27.7	38.7	44.9	45.3
	22°C	15.3	19.3	24.3	30.5	42.2	49.3	49.2
50% Fly Ash	5 °C	0.7	7.8	12.3	21.0	30.0	45.2	45.5
	14°C	5.0	12.6	15.5	21.7	33.5	39.8	39.5
	22°C	10.9	16.9	18.7	24.9	41.4	45.7	46.7

* Average of 3 cylinders
** Average of 2 cylinders

Table 7 - Chloride Permeability of Concrete

Curing Condition	Chloride-ion Penetration, coulombs			
	Control	30% Fly Ash	40% Fly Ash	50% Fly Ash
5°C	2759	980	593	229
14°C	5476	1393	788	584
22°C	5116	650	504	202

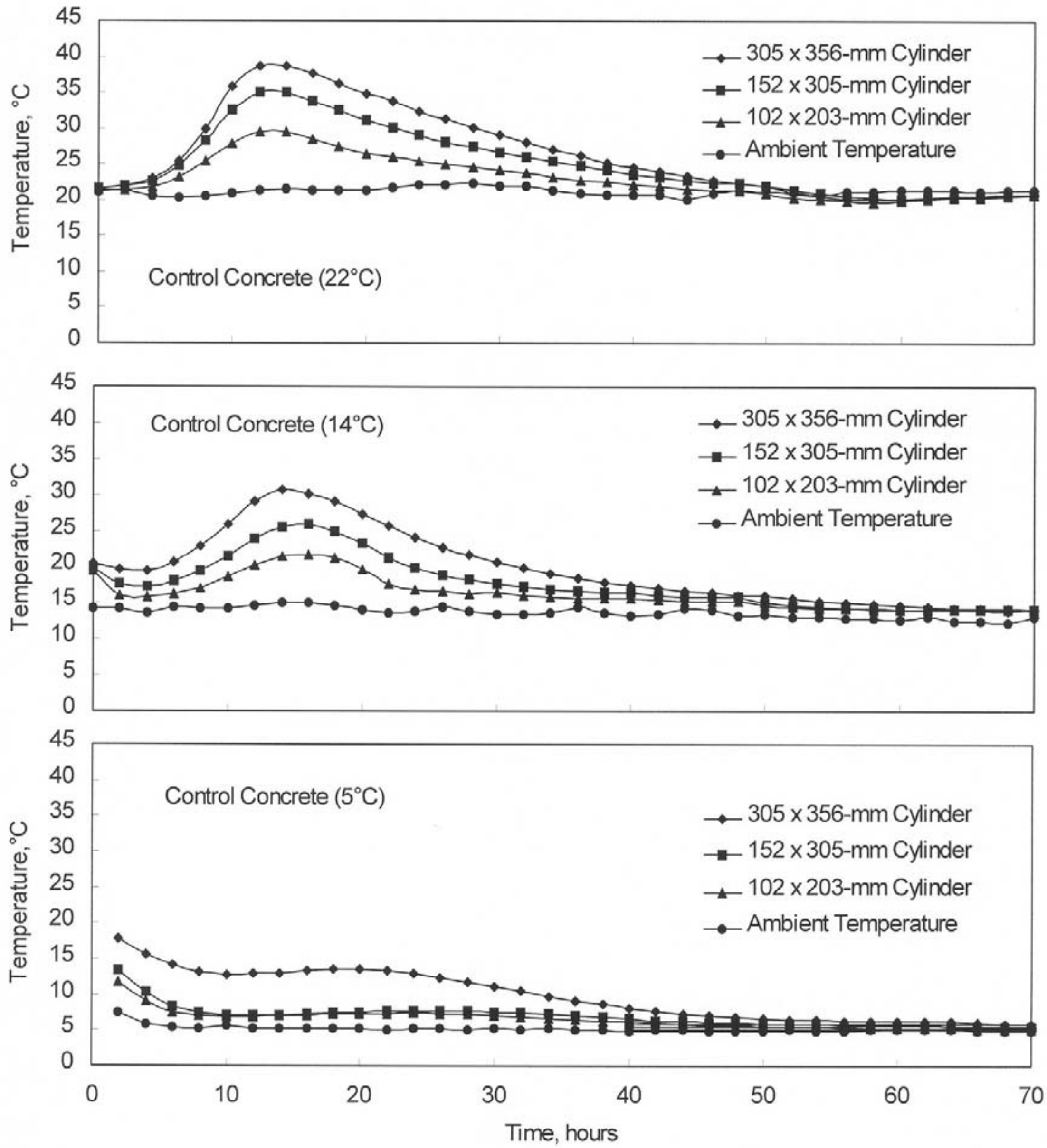

Fig. 1 - Temperature development of the control concrete at three different ambient temperatures

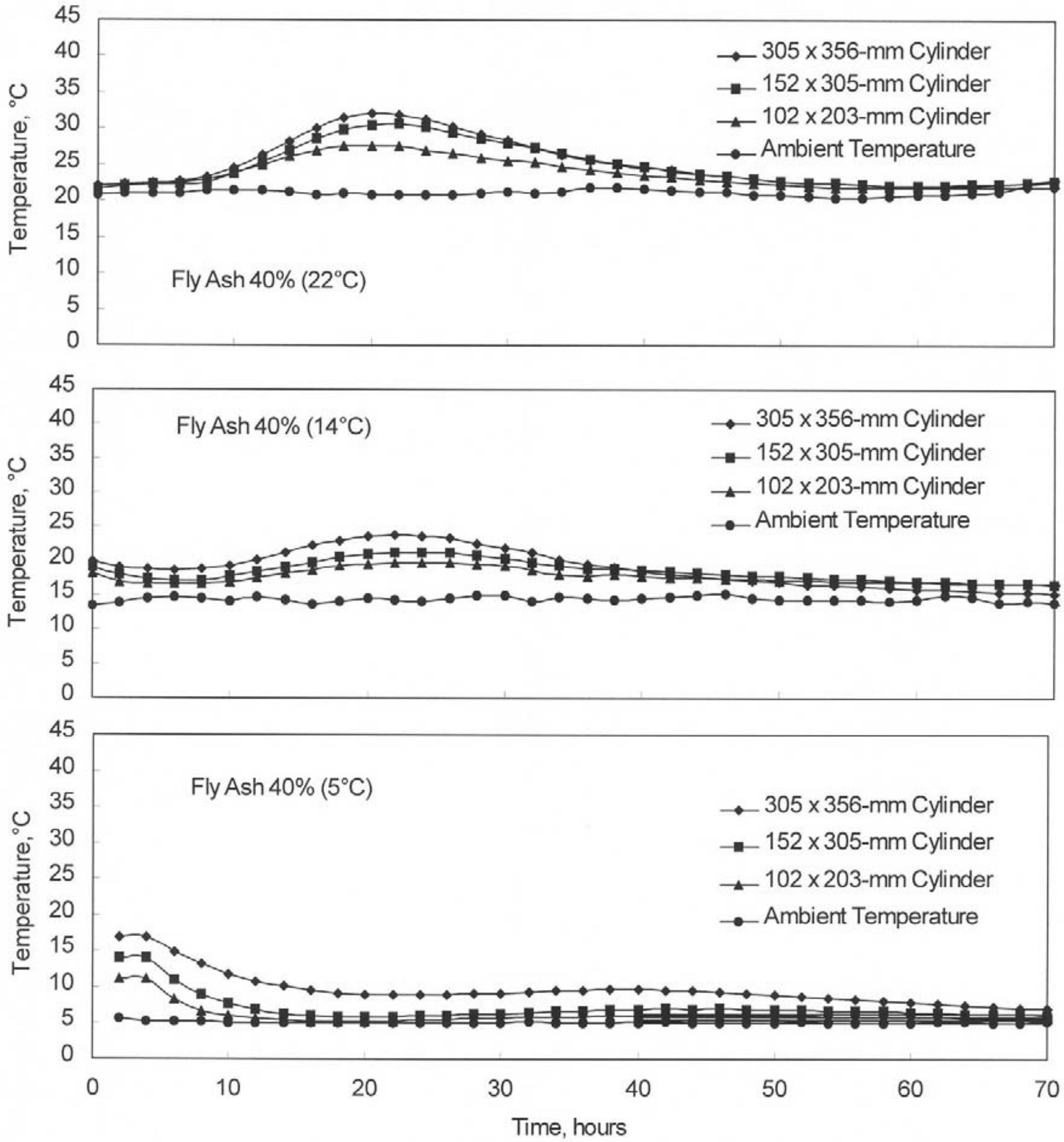

Fig. 2 - Typical temperature development of fly ash concrete at three different ambient temperatures

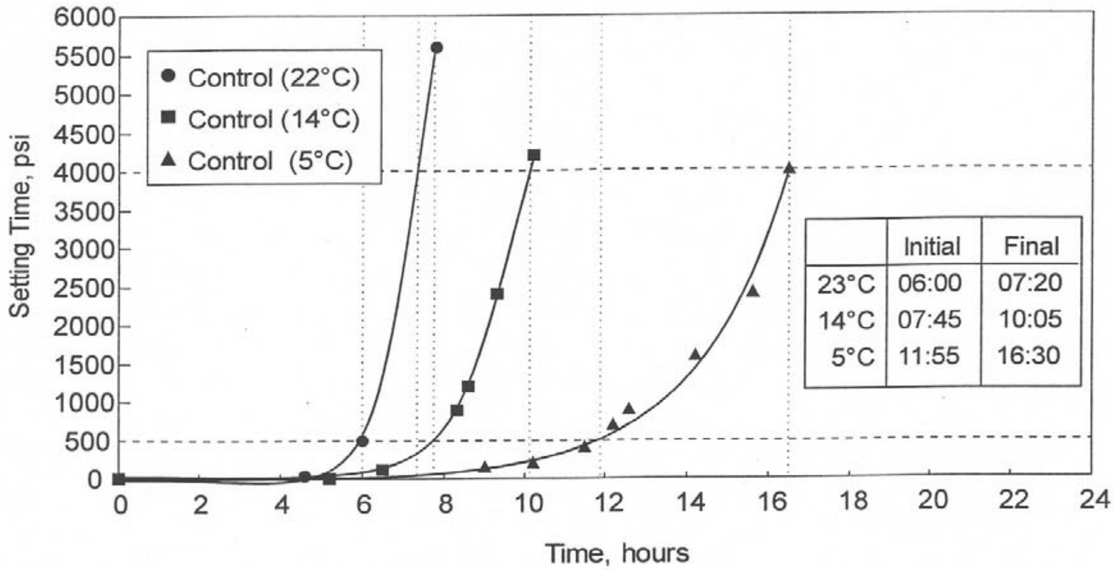

Fig. 3 - Setting time of the control concrete, exposed to three different ambient temperatures

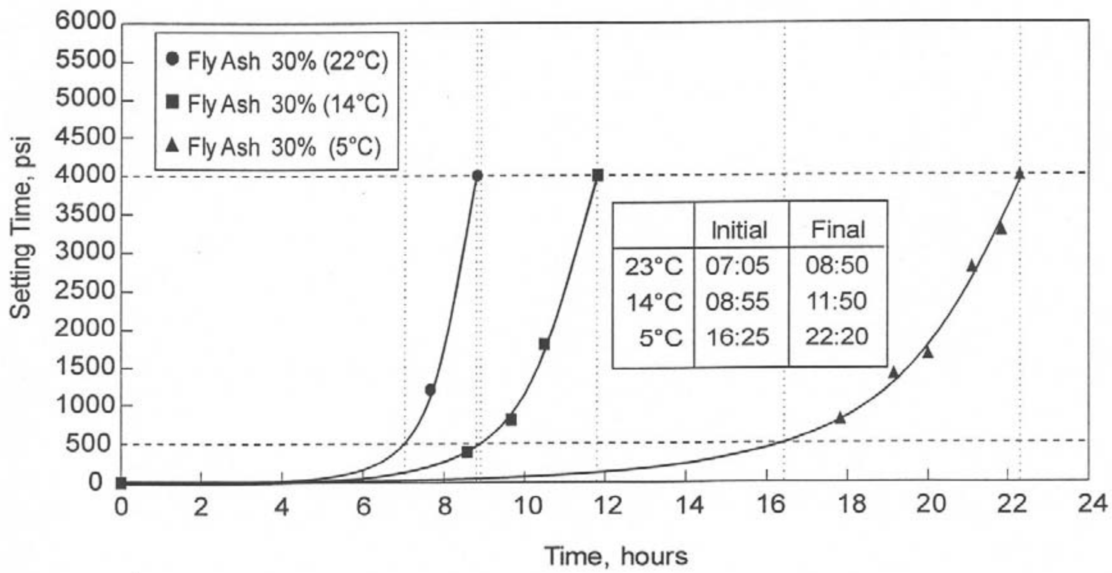

Fig. 4 - Setting time of the fly ash concrete at 30% replacement level, exposed to three different ambient temperatures

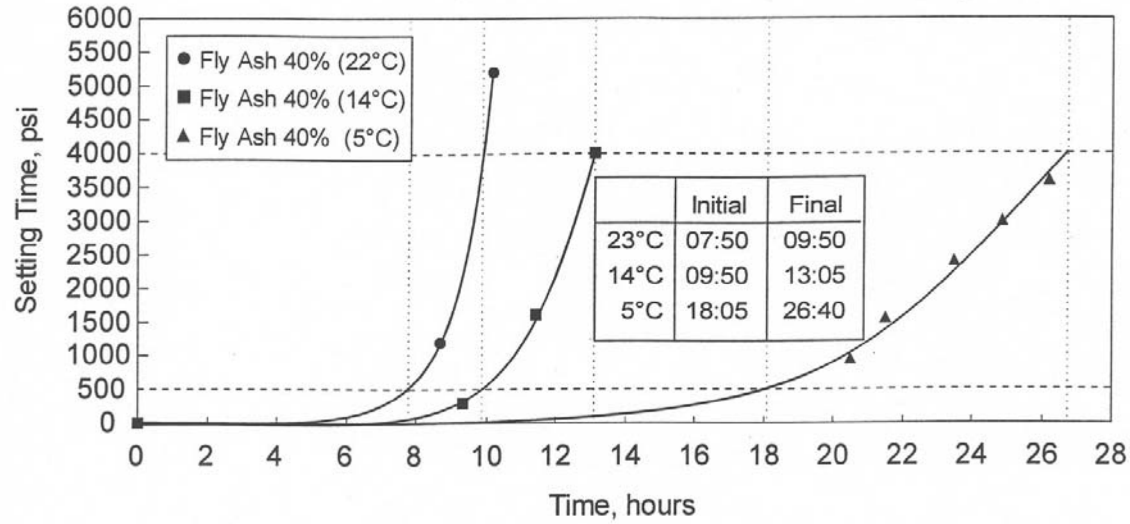

Fig. 5 - Setting time of the fly ash concrete at 40% replacement level, exposed to three different ambient temperatures

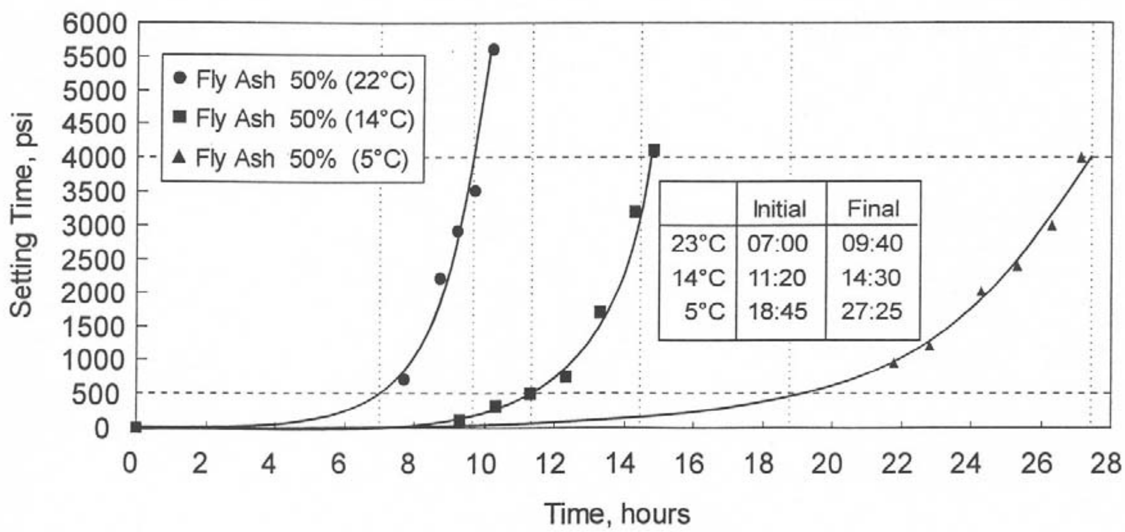

Fig. 6 - Setting time of the fly ash concrete at 50% replacement level, exposed to three different ambient temperatures

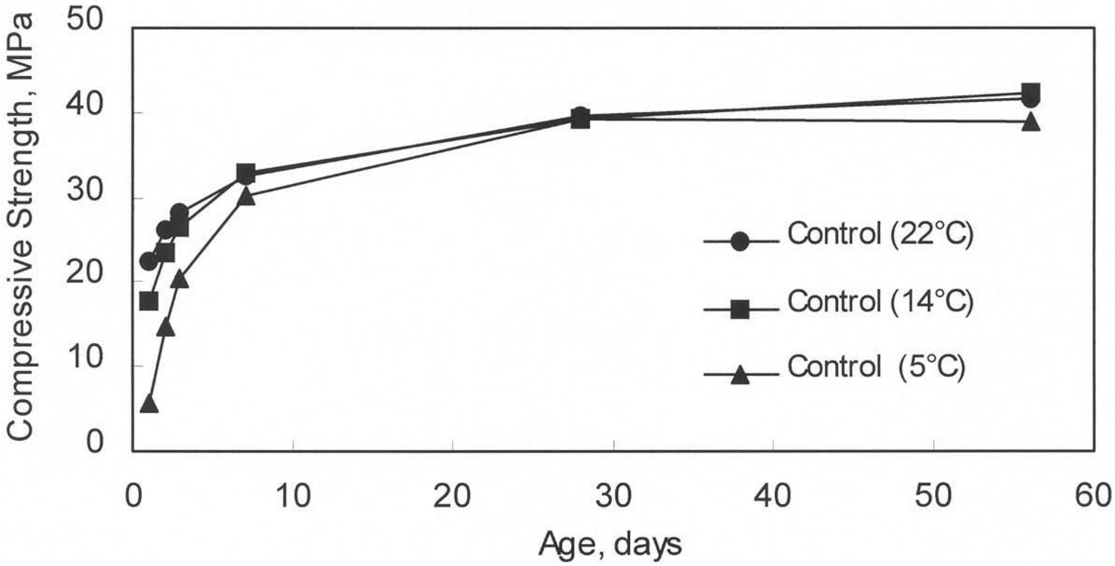

Fig. 7 - Compressive strength development of the control concrete, exposed to three different ambient temperatures

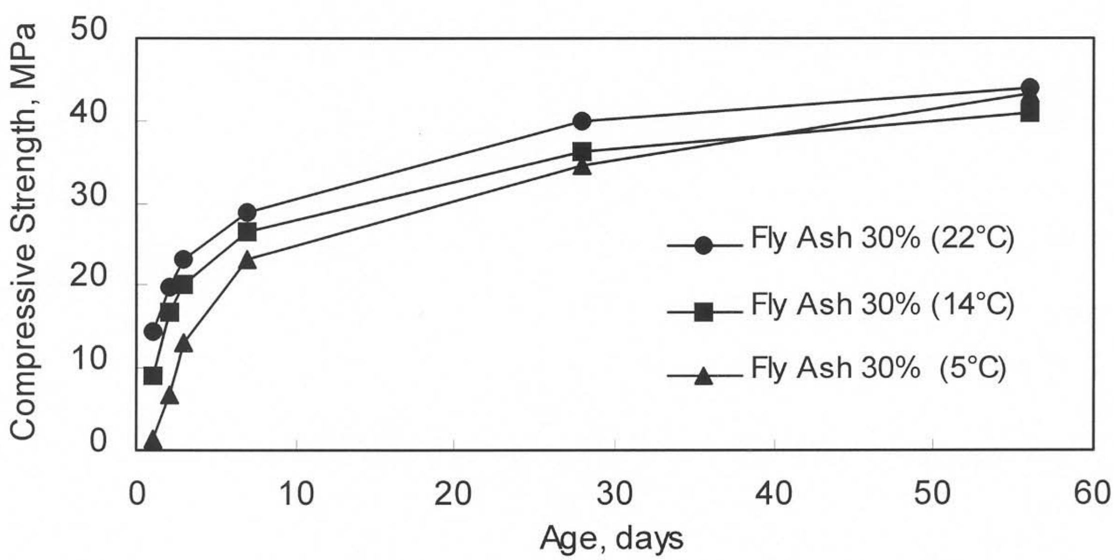

Fig. 8 - Compressive strength development of the fly ash concrete at 30% replacement level, exposed to three different ambient temperatures

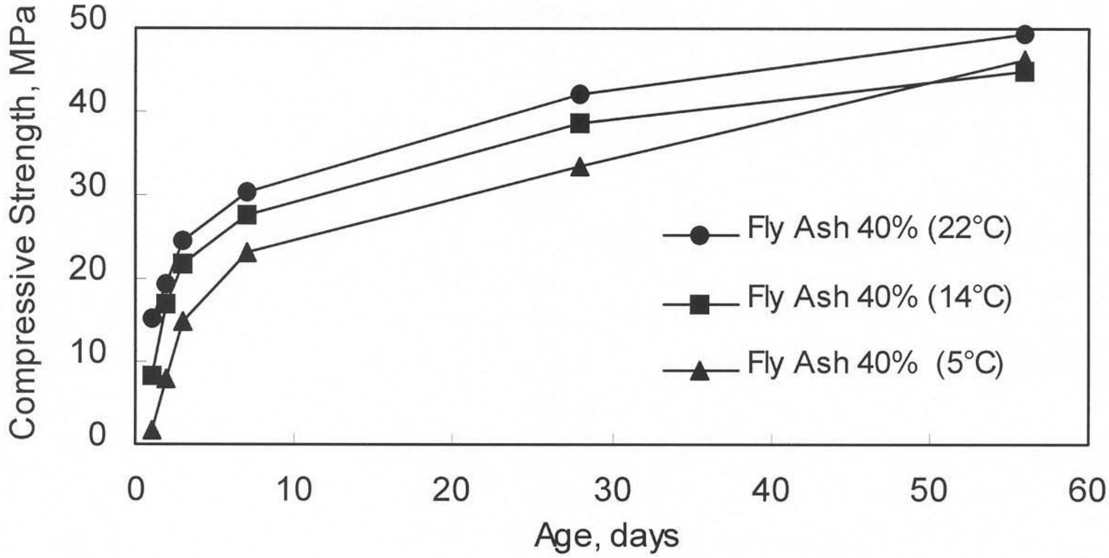

Fig. 9 - Compressive strength development of the fly ash concrete at 40% replacement level, exposed to three different ambient temperatures

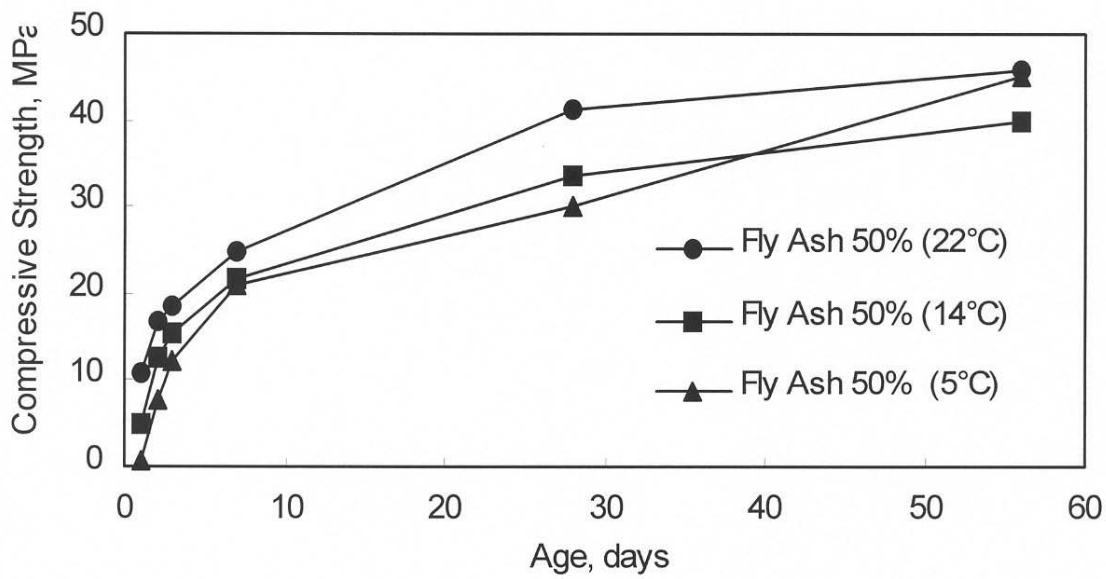

Fig. 10 - Compressive strength development of the fly ash concrete at 50% replacement level, exposed to three different ambient temperatures