SP 91-44

Strength and Heat Development in Concrete: Influence of Fly Ash and Condensed Silica Fume

by Magne Maage

Synopsis: In order to reduce energy, save raw materials and improve mechanical properties, different pozzolans are now commonly used in cement and concrete production. A comprehensive research program was undertaken where cement and concrete properties, influenced by fly ash and condensed silica fume in different combinations, were investigated. This paper presents their influence on strength and heat development.

The program included an ordinary portland cement and two blended cements with 10 % and 25 % fly ash respectively. The three cements were combined with 0 %, 5 % and 10 % condensed silica fume. Curing temperatures used were 5°C, 20°C and 35°C.

Condensed silica fume is very finely graded and the content of amorphous SiO_2 is very high. The pozzolana reaction starts therefore early, at 20°C from around 7 days, at 35°C from around 2 days. At 5°C, no pozzolana reaction was observed for the first 28 days. The pozzolana reaction from fly ash was found to be slower than the reaction from condensed silica fume, probably due to the coarser grinding and the lower SiO_2-content.

The compressive strength results indicated that the pozzolana reaction was more sensitive to the temperature than the reaction involving cement hydration alone.

The slow strength development of concrete when using fly ash in blended cements can be avoided by grinding the cements to a higher fineness. The effect on strength development when using condensed silica fume was approximately the same in all three types of cement investigated.

The heat development was higher in pure portland cement than in blended cements. However, when adding condensed silica fume, the heat development increased.

Maturity functions were found to be valid up to maturities corresponding to curing in 20°C for approximately 2 days.

Keywords: age-strength relation; blended cements; compressive strength; concretes; curing; fly ash; heat of hydration; silica; temperature.

Dr.eng. Magne Maage is Head of group Cement and Concrete Technology, Cement and Concrete Research Institute, The Foundation for Scientific and Industrial Research at the Norwegian Institute of Technology. He is a member of ACI and RILEM. His main interests are related to cement and concrete technology.

INTRODUCTION

In order to reduce energy cost, save raw materials and improve concrete properties, various pozzolanas are now commonly used in cement and concrete production. Often pozzolanas are added to concrete at a batch plant. In this investigation, however, the fly ash was added to the cement klinker in the grinding process. The cement was ground to a higher fineness when the fly ash content was increased. The condensed silica fume was added at the time of batching concrete.

This investigation is a part of a comprehensive concrete research program where silica fume and fly ash are combined. The program is sponsord by Norcem Cement A/S and Elkem A/S Chemicals.

SCOPE OF INVESTIGATION

The objective of this research program was to examine strength and heat development in concrete made of various blended cements compared with ordinary portland cement (OPC). Concrete mixes were cast and cured at different temperatures and various quantities of condensed silica fume were added. Adiabatic heat development was measured in the same concrete mixes. Based on maturity principles, expected strength development when curing at 5°C and 35°C was calculated.

CONCRETE MIXES

The concrete mixes were produced in the laboratory during the fall 1983 using a counter-current mixer. The total mixing time was 4 minutes, interrupted by 5 minutes waiting for possible false set, before the last minute of mixing.

Materials

Cement--Three different cement types produced in Norway were used as shown in Table 1. The physical properties and chemical analysis of the cements are given in Table 2.

Fly ash--A Danish Class F fly ash meeting the requirements of ASTM C618 was used in the cement production. The physical properties and chemical analysis are given in Table 2.

Condensed silica fume--Condensed silica fume from a Norwegian silicon alloy manufacturing plant was used. Its physical properties and chemical analysis are given in Table 2. The condensed silica fume was added in a slurry form.

Aggregates--The fine aggregate was a natural sand and the coarse fraction was a crushed basalt with maximum diameter up to 25 mm. Properties of the aggregates are given in Table 3.

Plasticizer--An aqueous lignosulphonate-based plasticizer with 40 % solid lignosulphonate and 60 % water, produced in Norway, was used.

Mix proportions

Eight series of concrete mixes were made for testing compressive strength at various temperatures as shown in Table 4. Each mix was produced three times at different temperatures (5°C, 20°C and 35°C). The correct temperatures in the concrete mixes just after mixing was reached by controlling the temperature of materials and equipment. Measured temperatures were within ± 1.0°C of the designed values.

The mix proportion details of the eight series are shown in Table 5. All the mixes were proportioned to give a compressive strength of 50 MPa after 28 days of curing in water at 20°C. As shown in Table 5 the strength was reached within acceptable limits except for mix no. 8.

Properties of fresh concret

Properties of fresh concrete mixed at 20°C are given in Table 5. At 5°C, the slump values were somewhat higher and somewhat lower at 35°C. The other properties were unaffected from a practical point of view.

SAMPLES AND TEST METHODS

Compressive strength

For testing the compressive strength of concrete, 100 mm cube specimens were cast in accordance with Norwegian Code NS 427 A. From casting to demolding, the specimens were stored in the molds wrapped in plastic bags. At 20°C and 35°C the samples were demolded after 24 hours and then stored in water at 20°C and 35°C respectively until the test age. At 5°C the samples had to be in the molds for 48 hours before demolding and storing in water at 5°C. Two cubes from each mix and temperature were tested in compression at each of 16 hours, 1, 3, 7, 14 and 28 days. The testing was carried out in accordance with NS 427 A, which is comparable to ASTM C39.

Heat development

Heat development was measured by the use of an adiabatic calorimeter, Tonindustrie 6010. The tested concrete volume was 4 liters and the testing lasted for 3 days. In this method, no heat is transferred to the surroundings. The temperature rise in the concrete can be used for calculating the heat of hydration when the specific heat capacity of the sample is known.

TEST RESULTS

Compressive strength

The compressive strengths are given in Table 6. At 5°C, the strength was too low to be tested after 16 hours. In order to have a better base for comparison, the values in Table 6 have been corrected with a factor equal to 50 MPa divided by the compressive strength at 28 days when curing at 20°C. The corrected compressive strengths are given in Table 7.

Heat development

In Table 8 some of the results from the adiabatic calorimetry measurements are given. The complete heat development curves for OPC with and without condensed silica fume are shown in Fig. 6.

DISCUSSION AND ANALYSIS OF TEST RESULTS

Compressive strength

In actual use the early strength is of greatest interest. However, the strength of concrete in most codes refers to the values obtained at 28 days after curing in water at 20°C. It is therefore of interest to study the early-age strength when the strength grade is constant.

Cement type--When fly ash is added during mixing of concrete the early-age strength is generally lower compared with the concrete without fly ash at the same strength grade (1, 2). This effect may be corrected by grinding the cement finer. In Fig. 1 it is shown that this is the case for the MP30-I concrete. The MP30-II concrete has somewhat lower strengths than the control P30 concrete. Based on this the Norwegian Cement producer, NORCEM, is now producing a new cement with 20 % fly ash ground to around 4500 Blaine. Concrete with this cement has a strength profile higher or more like that of MP30-I.

In the case of fly ash the pozzolanic reaction at normal temperature is too slow to improve the strength at early ages. A finer ground cement has to take care of the early strength and the fly ash will most likely improve the long-term strength if the curing conditions are suitable.

When curing in water at 5°C and 35°C respectively, the three cement types performed in approximately the same manner as shown in Fig. 2. The early relative strengths at 5°C are very low. However, at 28 days, the compressive strengths are at the same level as when curing at 20°C. The early relative strengths at 35°C are high, but after 3 days the strengths are at the same level as when curing at 20°C. The MP30-II concrete is most sensitive to the temperature, due to the highest fly ash content.

Condensed silica fume--Condensed silica fume is much finer and more reactive than fly ash. At normal temperatures the pozzolanic reaction starts at about 7 days. For a constant strength grade, the early strength will therefore be reduced as shown in Fig. 3. The reduction seems to be the highest in the concrete mixes with fly ash cement.

When curing in water at 5°C and 35°C respectively, the three cement types performed in approximately the same manner with condensed silica fume as shown in Fig. 4. At 5°C, the compressive strengths are lower than the corresponding strengths when curing at 20°C. This is true also after 28 days. The reason for this is that the pozzolanic reaction in condensed silica fume is almost non existant of low temperatures. When curing at 35°C , the early-age strengths are high.A comparison between Figs. 2 and 4 shows that the strengths at 35°C are higher in Fig. 4 than in Fig. 2. A reason for this is that the pozzolanic reaction when using condensed silica fume is accelerated by the temperature.

A comparison between Figs. 2 and 4 also shows that the pozzolanic reaction in condensed silica fume is more sensitive to the temperature than the reaction in fly ash.

In Fig. 5, it is also shown that the strength development in concrete with 10 % condensed silica fume is slowed down of the beginning by the use of the silica fume compared to concrete without silica fume. When curing at 35°C, the period of slow strength gain was around 3 days. At lower temperatures than 20°C, strength gain at slower rate will last more than 28 days.

Similar findings for other strength grades with and without condensed silica fume in ordinary portland cement concrete have been reported in (3).

Heat development

Heat development in concrete is of great interest, especially in winter concreting and when massive structures are cast.

In Fig. 6 the complete adiabatic temperature development curves for concretes with OPC are shown. When using the two other types of cement, curves similar to those shown in Fig. 6 were obtained. Table 8 shows that the P30 cement is generating more heat than the cements with fly ash the first three days. No significant difference was found between the two fly ash cements. Data in Table 8 shows that the concretes with 10 % condensed silica fume produce more heat per kg of cement plus condensed silica fume than without silica fume. This is shown in Fig. 7 where the results from Fig. 6 are used. This effect has also been reported in cement paste when tested in isothermal calorimeter (4). Similar findings have also been reported for concrete (7).

Fig. 7 shows that cement without condensed silica fume generate more heat per kg of cement the first 24 hours than cement and 10 % silica fume. After 24 hours the opposite situation was found. It has been reported that the reaction between C_3S and water was accelerated by adding silica fume (8) and that the total heat development was increased (9).

Maturity calculations

The maturity of a concrete is a function of time and temperature. This is also correlated to the strength of the concrete. By knowing the time and temperature history for a concrete the first days, its strength can be calculated.

A number of maturity functions have been presented in the literature. Reviews of interesting functions are presented in (3, 5).

Maturity calculations in this paper will be based on the temperature function presented in (6). The temperature function $f(\Theta)$ is based on Arrhenius equation:

$$f(\Theta) = \{\exp \frac{E(\Theta)}{R} \left(\frac{1}{293} - \frac{1}{273 + \Theta}\right)\} \qquad [1]$$

where $E(\Theta)$ = activation energy for the hydration process
R = gas constant = 8.314 J/mol K
Θ = curing temperature, ^{o}C.

Based on Danish cements, the activation energy was found to be

$$E(\Theta) = 33\,500 + 1\,470\,(20 - \Theta), \quad \text{J/mol for } \Theta < 20^{o}C$$
$$E(\Theta) = 33\,500 \quad , \quad \text{J/mol for } \Theta > 20^{o}C$$

and the temperature function is consequently 0.29 at $5^{o}C$ and 1.95 at $35^{o}C$.

The correlation between compressive strength and equivalent curing time at 20°C (t_{20}) in (6) is found to be

$$f_c = f_{c\infty} \cdot \exp \left[- \left(\frac{t_e}{t_{20}}\right)^{\alpha} \right] \qquad [2]$$

where f_c = compressive strength at time t_{20} (hrs)
$f_{c\infty}$ = compressive strength at long time curing
t_e = time constant (hrs)
t_{20} = equivalent curing time at 20°C
α = curve fitting constant

The three constant $f_{c\infty}$, t_e and α can be calculated by an iteration process. The result of the iteration process for concrete without condensed silica fume cured at 20°C is shown in Fig. 8. No similar cure for concrete containing condensed silica fume is shown in Fig. 9 because equation [2] is not suitable in this case.

Compressive strengths calculated to equivalent curing time at 20°C according to equation [1] are shown in Fig. 8 for concrete without silica fume cured at 5°C and 35°C respectively. When curing at 35°C, the maturity calculations resulted in a relatively good correlation until around 2 days equivalent curing time at 20°C and until around 3 days equivalent curing time when the curing temperature was 5°C.

For concrete with 10 % condensed silica fume, approximately the same limiting equivalent curing times as in concrete without silica fume were found as shown in Fig. 9.

Comparing the results shown in Fig. 8 and 9 it is seen that curing at 5°C results in a better correlation between calculated and tested compressive strengths than curing at 35°C. When curing at 35°C the calculated equivalent compressive strengths are too low in concrete without condensed silica fume and too high in concrete with 10 % condensed silica fume. The different performance of concrete with and without condensed silica fume is a result of the acceleration of the pozzolanic reaction in concrete with silica fume.

CONCLUSIONS

The investigations show that the strength development profile of concrete may be the same if the fineness cement is increased with increasing fly ash content. Also when curing at 5°C and 35°C respectively, the three types of cements tested performed in approximately the same manner,and the curing at 5°C and 20°C resulted in the same strength as after 28 days curing in water.

In case of condensed silica fume, the early-age strength was reduced, the maximum being for concrete made with blended cements. When curing in water at 5°C and 35°C respectively, the three cement types performed in approximately the same manner as far as strength development was concerned.

Heat development measurements showed that the ordinary portland cement generated more heat than the blended cements. In concretes with silica fume, the heat generation per kg of cement plus condensed silica fume was higher than without silica fume.

Maturity calculations showed that the concept was valid up to around 2-3 days equivalent curing times at 20°C both with and without condensed silica fume. Curing at 35°C resulted in different performence in concretes made with and without condensed silica fume.

ACKNOWLEDGEMENT

The results presented in this paper are a part of a more comprehensive research program on blended cements. The program is sponsored by NORCEM CEMENT A/S and Elkem a/s Chemicals.

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Table 1. Cement Types Investigated

Cement Type	Cement ASTM Type I	Fly ash Class F ASTM C618	Blaine Fineness cm^2/g
P30	100 %	0 %	3140
MP30-I	90 %	10 %	3690
MP30-II	75 %	25 %	4280

Table 2. Physical Properties and Chemical Analysis of Cement, Fly Ash and Condensed Silica Fume

	Cement			Fly Ash	Silica Fume
	P30	MP30-I	MP30-II		
Physical Properties					
Fineness:					
88 µm (retaining)	1.6 %	-	0.08 %	-	-
Surface area, Blaine, cm^2/g	3140	3690	4280	4000[1]	-
Surface area, BET, m^2/g	-	-	-	-	18
Compressive strength of 50 mm cubes at: 1 day	15.6	15.7	16.5	-	-
3 days	28.1	32.0	30.7	-	-
7 days	38.5	41.6	35.2	-	-
28 days	42.4	50.1	45.1	-	-
Chemical Composition					
Silicon dioxide (SiO_2)	20.7	23.0	28.6	54.1	94.7
Aluminum oxide (Al_2O_3)	4.7	6.6	10.3	27.5	0.1
Ferric oxide (Fe_2O_3)	3.2	3.4	5.1	5.3	0.4
Calcium oxide (CaO), total	63.7	59.0	49.7	5.0	0.4
Magnesium oxide (MgO)	2.3	2.6	2.5	1.7	0.6
Sulphur trioxide (SO_3)	3.2	3.3	3.4	-	0.1
Sodium oxide (Na_2O)	0.4	0.3	0.3	0.3	0.2
Potassium oxide (K_2O)	1.1	1.1	1.0	0.9	0.9
Loss of ignation	0.7	1.3	1.4	-	1.6

[1] Before ground into the klinker.

Table 3. Properties of Aggregates

	Coarse Aggregate	Fine Aggregate
Type	Crushed basalt	Natural sand
D_{max}	25 mm	16 mm
Fineness Modulus (ISO)	6.9	3.6
Specific Gravity	2820	2650

Table 4. Concrete Mix Program

Cement Type	Silica fume content	Mix No	Casting and Curing temperature, °C			Adiabatic heat development
			5°C	20°C	35°C	
P30	0 %	1	x	x	x	x
	10 %	2	x	x	x	x
MP30-I	0 %	3	x	x	x	x
	5 %	4	x	x	x	-
	10 %	5	x	x	x	x
MP30-II	0 %	6	x	x	x	x
	5 %	7	x	x	x	-
	10 %	8	x	x	x	x

Table 5. Mix Proportions and Properties of Fresh Concrete at 20°C.

Cement Type →		P30		MP30-I			MP30-II		
Mix No →		1	2	3	4	5	6	7	8
Cement Content	(kg/m^3)	330	255	345	300	250	335	300	250
Cond. Silica Fume	(kg/m^3)	-	25,5	-	15	25	-	15	25
Aggregate	(kg/m^3)	1930	1955	1950	1950	1940	1930	1922	1951
Plasticizer	(kg/m^3)	2.0	2.6	2.0	2.0	2.5	2.0	2.0	2.5
Water	(kg/m^3)	180	179	176	193	183	182	198	193
Slump	(cm)	11	13	12	15	13	10	13	14
w/c-ratio		0.55	0.70	0.51	0.64	0.73	0.55	0.67	0.77
w/c+s-ratio		-	0.64	-	0.61	0.66	-	0.64	0.70
Unit weight	(kg/m^3)	2440	2420	2470	2460	2400	2450	2430	2420
Air content	(%)	2.6	2.6	2.4	2.3	2.5	1.8	1.7	2.0
Compressive strength, 28 d, 20°C, water	(MPa)	50.4	53.6	52.0	50.1	51.7	47.7	47.1	41.6

1) An aqueous lignosulfonate-based plasticizer

Table 6. Compressive Strength Test Results

Cement Type	Temp. (°C)	Mix No	Silica content (%)	Compressive strength, MPa [1]					
				16 hrs	1 d	3 d	7 d	14 d	28 d
P30	5	1 2	0 10	- -	0.32 0.17	17.0 12.8	33.9 25.8	42.6 34.1	50.3 40.1
	20	1 2	0 10	12.3 9.7	23.4 16.1	35.0 29.0	42.8 36.3	46.2 45.1	50.4 53.6
	35	1 2	0 10	28.6 23.4	32.5 28.1	35.2 41.0	39.6 49.2	43.5 51.9	46.2 53.4
MP30-I	5	3 4 5	0 5 10	- - -	1.15 0.34 0.75	23.9 17.6 13.4	41.4 31.0 25.1	50.6 39.5 30.7	54.2 45.4 35.5
	20	3 4 5	0 5 10	15.4 11.2 8.1	27.6 15.9 13.8	40.1 28.9 25.6	44.0 38.9 34.4	48.8 44.2 34.9	52.0 50.1 51.7
	35	3 4 5	0 5 10	28.4 17.9 20.3	32.7 23.9 25.4	37.0 32.8 37.7	43.5 39.5 45.5	48.8 41.7 48.9	53.4 45.4 50.6
MP30-II	5	6 7 8	0 5 10	- - -	0.58 0.59 0.27	14.7 10.9 8.5	26.1 19.4 14.8	34.7 26.0 20.1	41.5 30.4 23.9
	20	6 7 8	0 5 10	8.8 5.7 3.5	22.1 13.5 10.9	30.6 23.9 18.5	37.4 29.7 24.3	42.2 38.4 33.4	47.7 47.1 41.6
	35	6 7 8	0 5 10	20.8 15.0 11.7	24.9 18.8 15.4	31.3 30.6 28.6	41.2 40.7 37.8	46.9 44.9 42.7	54.1 50.0 46.7

1) Mean of two cubes.

Table 7. Corrected Compressive Strengths 2)

Cement Type	Temp. (°C)	Mix No	Silica content (%)	Compressive strength, MPa 1)					
				16 hrs	1 d	3 d	7 d	14 d	28 d
P30	5	1 2	0 10	- -	0.32 0.16	16.9 11.9	33.6 24.1	42.3 31.8	49.9 37.4
	20	1 2	0 10	12.2 9.1	23.2 15.0	34.7 27.1	42.5 33.9	45.8 42.1	50.0 50.0
	35	1 2	0 10	28.4 21.8	32.2 26.2	34.9 38.2	39.3 45.9	43.2 48.8	45.8 49.8
MP30-I	5	3 4 5	0 5 10	- - -	1.11 0.34 0.73	23.0 17.6 13.0	39.8 30.9 24.3	48.7 39.4 29.7	52.1 45.3 34.3
	20	3 4 5	0 5 10	14.8 11.2 7.8	26.5 15.9 13.3	38.6 28.8 24.8	42.3 38.8 33.3	46.9 44.1 42.5	50.0 50.0 50.0
	35	3 4 5	0 5 10	27.3 17.9 19.6	31.3 23.9 24.6	35.6 32.7 36.5	41.8 39.4 44.0	46.9 41.6 47.3	51.3 45.3 48.9
MP30-II	5	6 7 8	0 5 10	- - -	0.61 0.63 0.33	15.4 11.6 10.2	27.4 20.6 17.8	36.4 27.6 24.2	43.5 32.3 28.7
	20	6 7 8	0 5 10	9.2 6.1 4.2	23.2 14.3 13.1	32.1 25.4 22.2	39.2 31.5 29.2	44.2 40.8 40.1	50.0 50.0 50.0
	35	6 7 8	0 5 10	21.8 15.9 14.1	26.1 20.0 18.5	32.8 32.5 34.4	43.2 43.2 45.4	49.2 47.7 51.3	56.7 53.1 56.1

1) Mean of two cubes.

2) Correcting factor is equal to 50 MPa divided by the compressive strength at 28 days when curing at 20°C in water.

Table 8. Heat Development Measurements

Cement Type	Mix No	Silica content (%)	Temp. (°C) at		Heat development after 3 days in kJ pr kg cement + silica fume
			Starting	3 days curing	
P30	1	0	19.0	65	319.0
	2	10	18.5	68	429.3
MP30-I	3	0	19.0	60	285.9
	5	10	19.0	59	349.8
MP30-II	6	0	18.5	60	291.0
	8	10	18.5	58	337.9

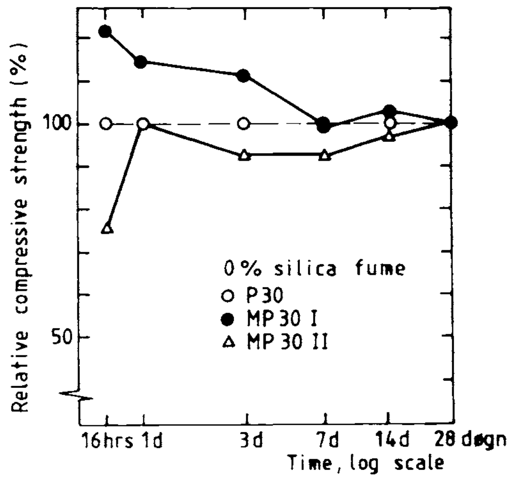

Fig. 1. Relative compressive strength when curing in water at 20°C for the cements MP30-I and MP30-II compared to cement P30.

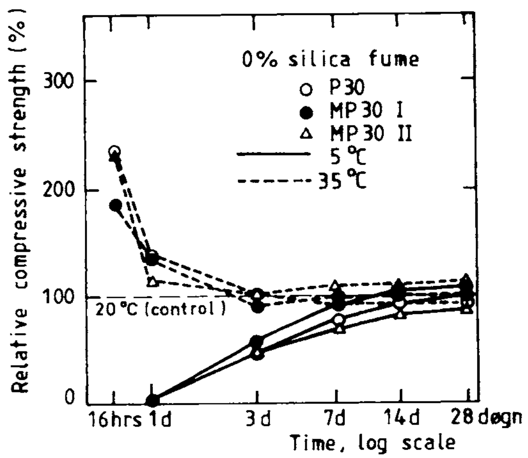

Fig. 2. Relative compressive strength when curing in water at 5°C and 35°C respectively compared to curing in water at 20°C.

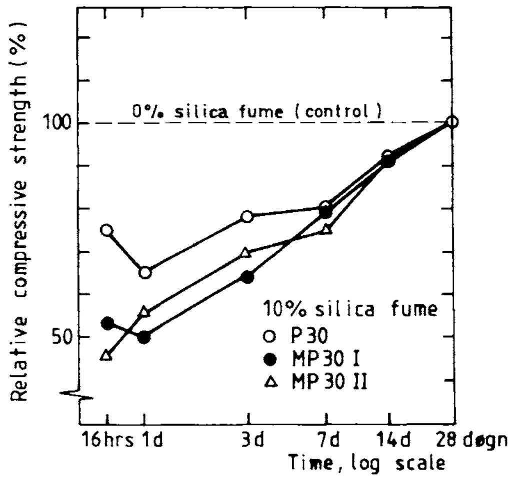

Fig.3. Relative compressive strength for concrete with 10 % condensed silica fume when curing in water at 20°C compared to concrete without silica fume cured at the same temperature.

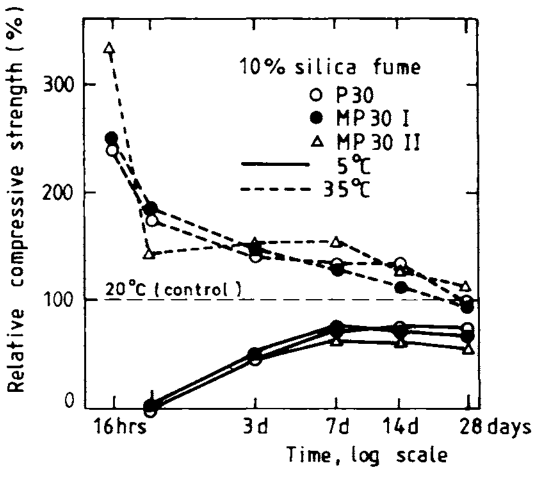

Fig. 4. Relative compressive strength when curing in water at 5°C and 35°C respectively compared to curing in water at 20°C.

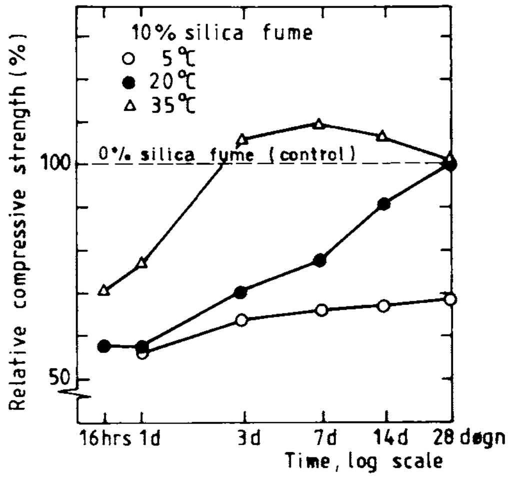

Fig. 5. Compressive strength in concrete with 10 % condensed silica fume cured in water at 5°C, 20°C and 35°C respectively in % of strength in concrete without silica fume cured at the same temperatures in water. Mean of concrete with the three sements.

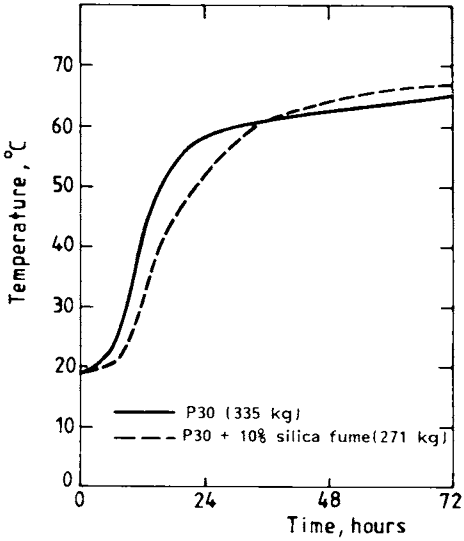

Fig. 6. Adiabatic temperature measurements in concrete with P30-cement with 0 % and 10 % condensed silica fume. Compressive strength after 28 days standard curing was around 40 MPa and consequently the cement content was different in the two concretes.

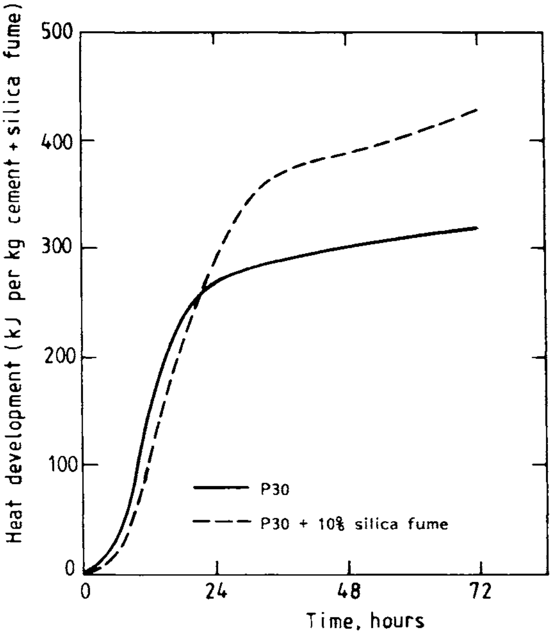

Fig. 7. Adiabatic heat development measurements in concrete with P30-cement with 0 % and 10 % condensed silica fume.

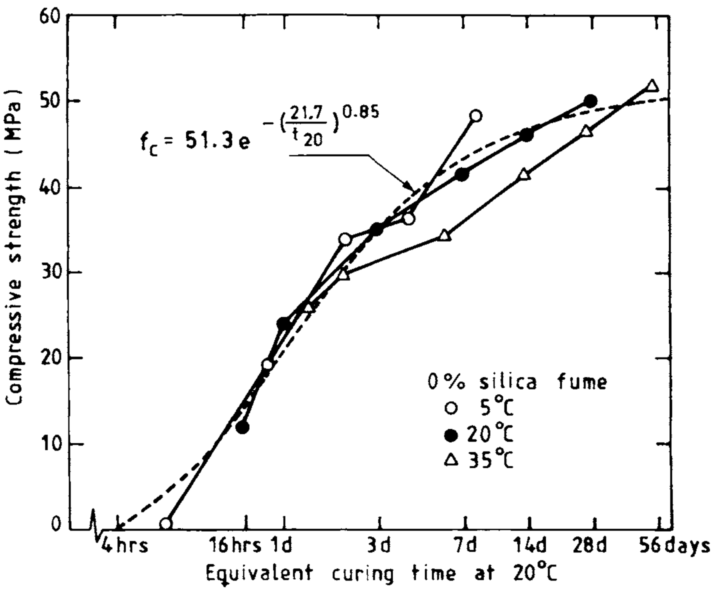

Fig. 8. Compressive strength at 20°C and at 5°C and 35°C calculated to equivalent curing time at 20°C according to Freisleben Hansen and Pedersen's equation. Mean of concrete with the three cements without condensed silica fume.

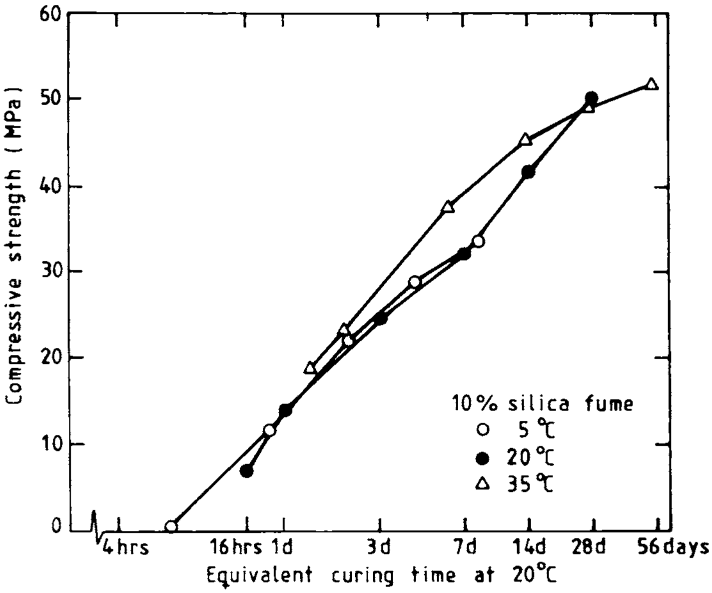

Fig. 9. Compressive strength at 20°C and at 5°C and 35°C calculated to equivalent curing time at 20°C according to Freisleben Hansen and Pedersen's equation. Mean of concrete with the three cements and with 10 % condensed silica fume.