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THE EFFECT OF SILICA FUME ON THE PRINCIPAL PROPERTIES OF CONCRETE

Bertil Persson

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Abstract

In this article an experimental and numerical study of the long-term interaction between silica fume and Portland cement in concrete subjected to air, water and sealed curing is outlined. For this purpose about 2000 kg of eight qualities of concrete were studied at 4 different ages, each over a period of 90 months. Half of the concretes contained 10% silica fume. Parallel studies of strength, heat of hydration, hydration and internal relative humidity were carried out. New and original results and analyses of the interaction between Portland cement and silica fume related to compressive strength, split tensile strength, hydration and internal relative humidity are presented. The project was carried out between 1989 and 1996.

Key words: Compressive strength, Heat of hydration, Hydration, Self-Desiccation, Silica fume, Split tensile strength, Strength.

1 Introduction

Reports have been presented over the last years dealing with the decrease of strength of concrete over time due to content of silica fume, Larsen et al (1993). Most of the observations have been explained by different moisture conditions in the concrete when the compressive tests were carried out, Perraton et al (1994). The decrease of split tensile strength compared to compressive strength in a concrete with silica fume has been related to the pronounced basic (autogenous) shrinkage that occurred in a concrete with silica fume, Persson (1997). Finally, the development of hydration differs substantially between concretes with and without silica fume, Persson (1996A). To complete the pozzolanic reaction between silica fume and Portland cement about 16% silica fume is required calculated on the basis of reacted amount of cement, Peterson (1976). At low water-cement ratio, $w/c < 0.30$, some cement is left unreacted which thus means a surplus of silica fume exists to complete the pozzolanic reaction provided that 10% silica fume was added as calculated from the cement content. Since no additional water is consumed during the pozzolanic reaction, no additional chemical shrinkage occurs, Persson (1996B). The additional autogenous shrinkage is explained by the extended depression in the pore water when silica fume is used, Persson (1996B).

2 Previous research on the effect of silica fume on properties of concrete

2.1 Hydration

An attempt has been made to estimate the ultimate heat of hydration and the rate of hydration as affected by w/c, Figure 1, Dilger and Wang (1995A), Wang and Dilger (1995B). The following correlation was obtained for total heat of hydration, Q (kJ/kg):

$$Q = 445 \cdot (w/c)^{0.4} \quad (1)$$

Superplasticiser, s.p., is normally required when silica fume, s.f., is added to the concrete, especially at low w/c. Addition of s.p. affects hydration and temperature rise. Figures 2 and 3 show the retarding effect, Cook et al (1992), Burg and Ost (1994). Figure 4 shows a substantial delay of rate of heat of hydration due to the effect of the added s.p., Swamy et al (1994).

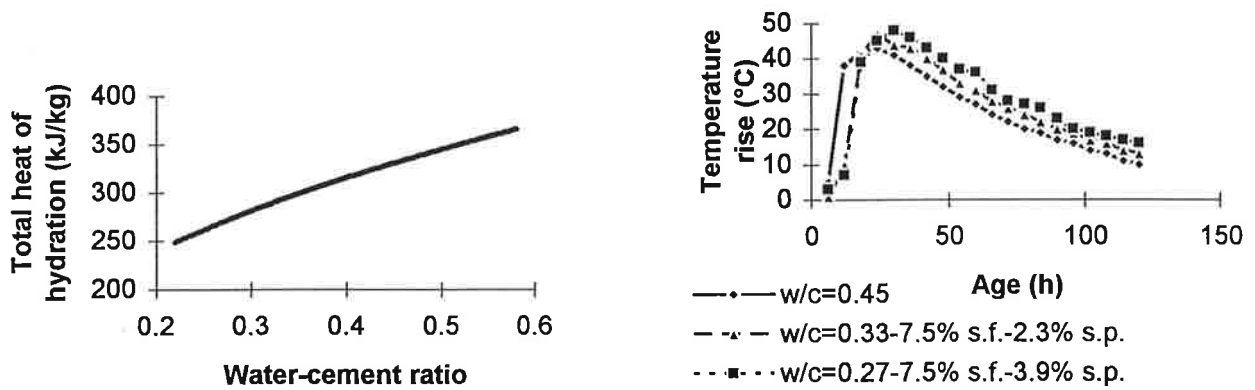


Figure 1 Total heat of hydration versus w/c.

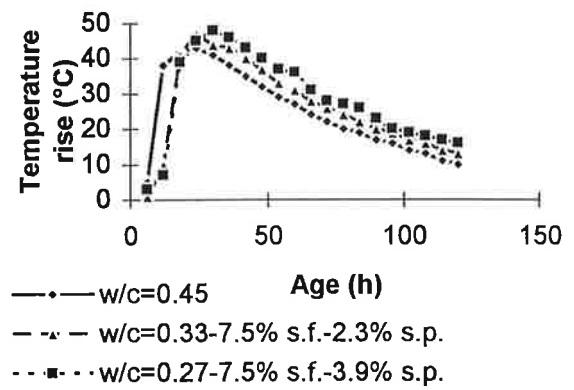


Figure 2 Temperature rise versus age.

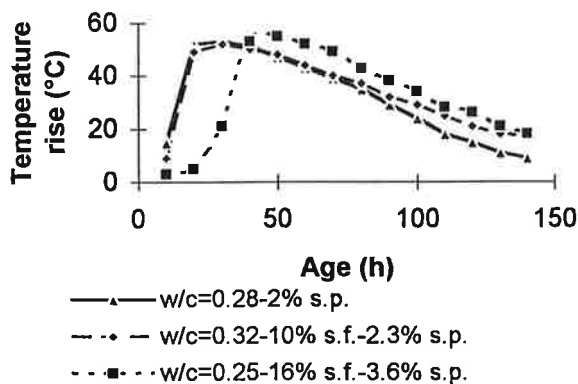


Figure 3 Temperature rise versus age.

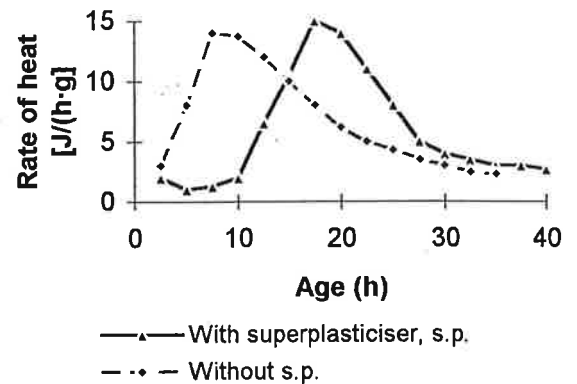


Figure 4 Rate of heat versus age.

2.2 Strength

The efficiency factor of silica fume, k_s , on properties of concrete is defined in equation (1), Persson (1996A). Figure 5 shows efficiency factors around $k_s = 7$ when 5-10% silica fume was added to the concrete, Babu and Prakash (1994), according to literature and experiments.

$$(w/c)_{\text{eff}} = w / (c + k_s \cdot s) \quad (2)$$

Especially when the addition of silica fume, s.f., was supplemented by quartzite filler, the efficiency factor of s.f. related to the strength, k_s , of the concrete became high. Figure 6 shows strength versus w/c of concrete with and without s.f., Penttala and Wirtanen (1997).

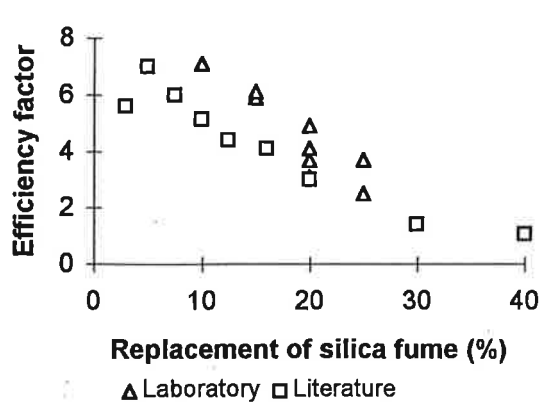


Figure 5 Efficiency factor of silica fume versus replacement of silica fume.

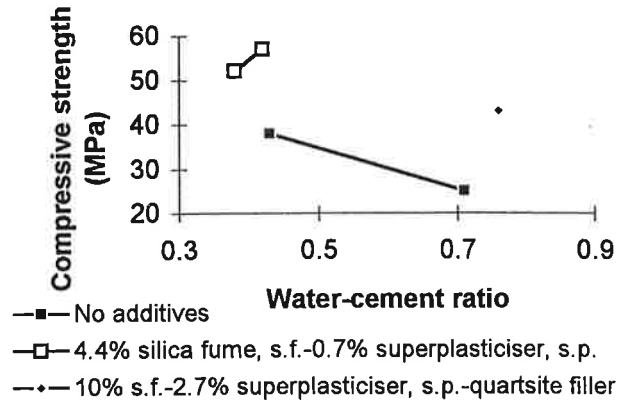


Figure 6 Strength versus w/c with different silica fume content.

3 Experiments

3.1 Material and preparation of specimens

Table 1 show the chemical composition of the cement, Persson (1996A). Table 2 shows the number of specimens that were studied, in all 1854 specimens. Table 1 shows the mix proportions of the tested concretes, Persson (1996A). The concrete was poured in the shape of a disc, 1 m in diameter and 0.1 m thick. The surface was sealed with a minimum of 2 mm epoxy resin. The specimens consisted of drilled cores with a diameter of 40 mm and a length of 80 mm. The heat of hydration was studied on 50 kg concrete in the shape of a cylinder cast in a remaining mould of steel-sheeting, Persson (1992).

3.2 Methods

About 900 cores were studied related to strength. During testing interlayers of hardboard were used. About 230 measurements of $\emptyset$ in the concrete were carried out. High-capacity probes were used. The measurement period was 22 h. The probes were calibrated, ASTM E 104-85. Hydration was studied by 648 measurements of weight losses during ignition between 105°C and 1050°C. Compensation was made for losses of weight of the different materials, Byfors (1980). The heat of hydration was obtained by semi-adiabatic experiments, Smeplass (1988).

4. Result and Analyses

4.1 Self-Desiccation, $\emptyset$

Figure 8 shows the self-desiccation, $\emptyset$, during sealed curing, Persson (1996C). The results coincided well with research carried out by others, Norling Mjörnell (1993). Figure 9 shows the efficiency factor of silica fume related to self-desiccation, k_{se} , equation (3), Persson (1996C).

$$k_{se} = 17.2 \cdot (0.004 \cdot t - 1) \cdot (w/c) - 0.026 \cdot t + 9.2 \quad \{\text{limits of age: } 28 < t < 450 \text{ days}\} \quad (3)$$

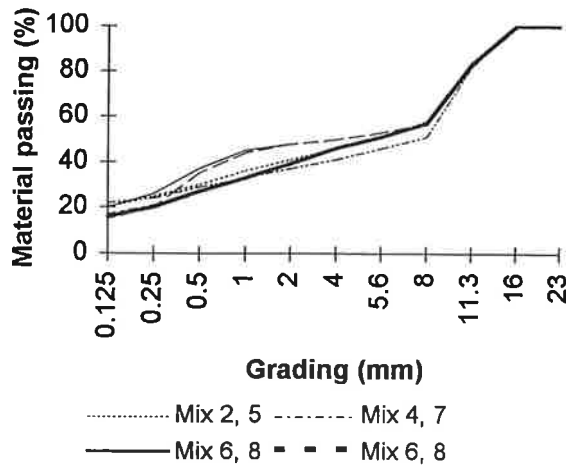


Figure 7 Grading of particles in fresh concrete

Table 2 - Number of measurements (m=months)

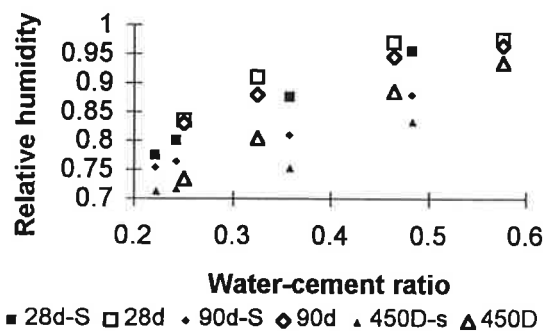
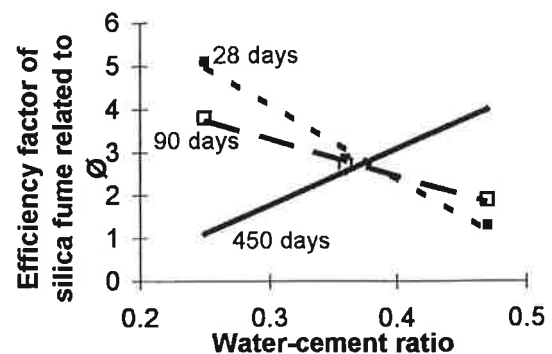
Parameter	1 m	3 m	5 m	15 m	90 m
f_c	144	144	72	144	144
f_{sp}	72	72	-	72	72
Hydration	144	144	72	144	144
$\emptyset$	72	72	-	72	18
Total	432	432	180	432	378

Table 1 - Chemical composition of cement.

Analysed properties (%):	
CaO	64.6
SiO ₂	21.8
Al ₂ O ₃	3.34
Fe ₂ O ₃	4.39
MgO	0.84
K ₂ O	0.62
Na ₂ O	0.07
Alkali	0.48
SO ₃	2.23
CO ₂	0.14
Free CaO	1.13
Mineralogical properties (%):	
C ₂ S	22.5
C ₃ S	53.0
C ₃ A	1.42
C ₄ AF	13.4
Physical properties:	
Ignition losses	0.63%
Blaine	325 m ² /kg
Density	3180 kg/m ³

Table 2 Mix proportions of tested concretes (kg/m³ dry material).

Littera	1	2	3	4	5	6	7	8
Quartzite sandstone 8-12 mm	1358	1306	1306	1214	1158	1150	1153	1145
Natural gravel 0-8 mm	525	630	549	723	730	846	825	812
Cement, c, low-alkaline, 325 m ² /kg	484	456	476	400	389	303	298	299
Silica fume, s, granulated, 17.5 m ² /g	48		48		39		30	
Superplasticiser, naphthalene sulphate	13.3	8.84	7.78	3.35	3.07	3.01	2.13	
Water-cement ratio, w/c	0.22	0.25	0.24	0.33	0.36	0.47	0.48	0.58
Air content (%)	0.95	1.5	0.8	1.4	1.1	1.1	0.95	0.75
28-day strength (cylinder, MPa)	112	96	115	74	92	56	66	38
90-day strength (cylinder, MPa)	133	107	124	90	103	66	77	45
450-day strength (cylinder, MPa)	143	130	142	96	106	75	78	49

Figure 8 $\emptyset$ after self-desiccation versus w/c. Symbols: d= days' age; S= 10% silica fume.Figure 9 Efficiency factor of 10% silica fume related to self-desiccation. $\emptyset$ = relative humidity

4.2 Compressive strength

Figure 10 shows the strength with sealed curing, Persson (1996A). Figure 11 shows the efficiency factor, k_{sc} , related to compressive strength, Persson (1996C).

$$k_{sc} = 112 \cdot t^{-0.40} \cdot e^{(0.00073 \cdot t - 5.23) \cdot w/c} \quad \{\text{limits of age: } 28 < t < 450 \text{ days}\} \quad (4)$$

The efficiency factor, k_{sc} , related to compressive strength decreased substantially over time. Tests at seven years' age have shown an even lower efficiency factor, k_{sc} , for silica fume. After 7 years the efficiency of silica fume on compressive strength became zero or slightly negative, Persson (1997C). The reason for this was probably the self-desiccation of the concrete that was pronounced in concretes with silica fume, Persson (1997A), almost stopping the hydration.

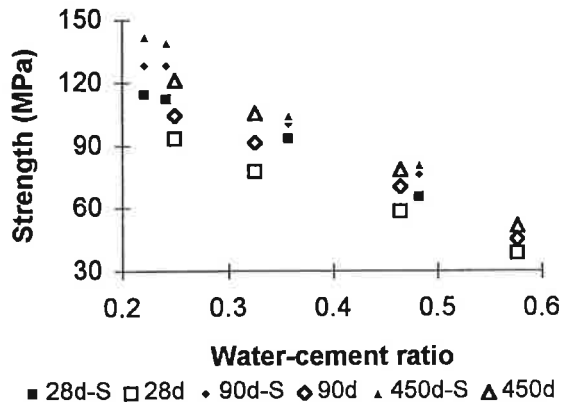


Figure 10 Compressive strength versus w/c. Symbols: d= days' age; S= 10% silica fume.

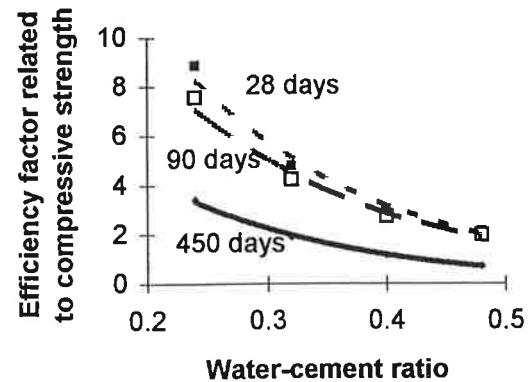


Figure 11 Efficiency factor of 10% silica fume related to compressive strength.

4.3 Split tensile strength

Figure 12 shows the split tensile strength with sealed curing, Persson (1996A). Figure 13 shows the efficiency factor of silica fume related to split tensile strength, k_{st} . After 15 months' age the efficiency factor of tensile strength remained at $k_{st} = 1$, at least until 90 months' age.

$$k_{st} = 12.4 \cdot e^{-2.5 \cdot w/c} \quad \{t = 28 \text{ days}\} \quad (5)$$

$$k_{st} = (3.6 - 0.0031 \cdot t) \cdot (w/c) + 0.0005 \cdot t \quad \{\text{limits of age: } 90 < t < 450 \text{ days}\} \quad (6)$$

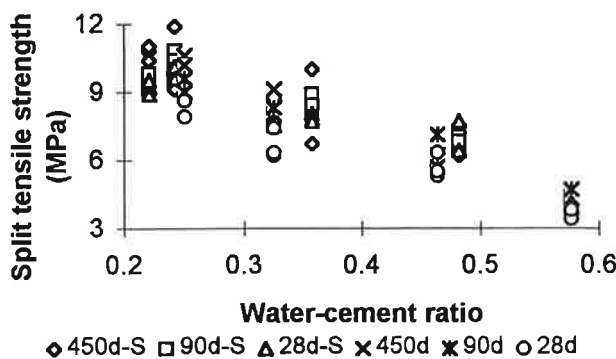


Figure 12 Split tensile strength versus w/c. Symbols: d= days' age; S= 10% silica fume.

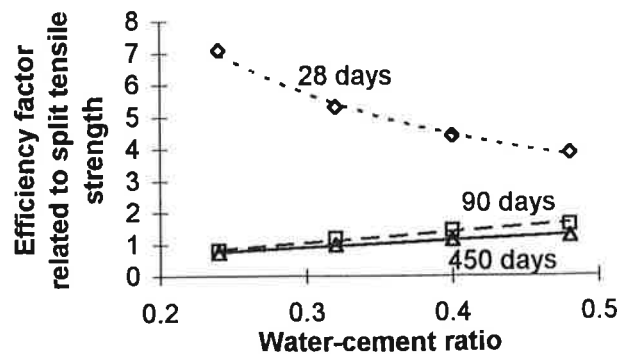


Figure 13 Efficiency factor of 10% silica fume related to split tensile strength.

4.4 Hydration

The hydration of concrete related to w/c differed greatly between concretes with and without s.f., Figure 14. The efficiency factor of 10% silica fume, k_{wn} , became negative, Figure 15.

$$k_{wn} = 0.043 \cdot [\ln(t) + 30] \cdot \ln(w/c) - 0.006 \cdot t \cdot (1 - 0.01 \cdot t) - 0.71 \quad \{\text{limits of age: } 1 < t < 90 \text{ months}\} \quad (7)$$

k_{wn} denotes the efficiency factor of 10% silica fume related to hydration

$\ln(t)$ denotes the natural logarithm of the age of the concrete, t (months)

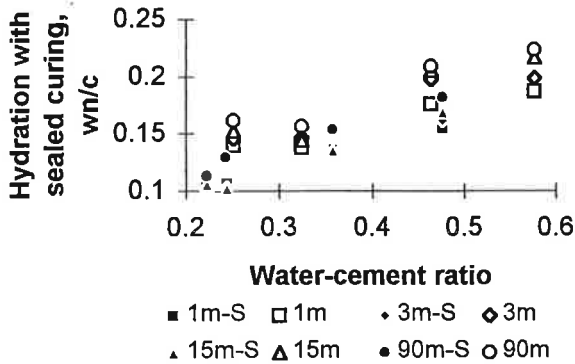


Figure 14 Hydration versus w/c. Symbols: m= months' age; S= 10% silica fume.

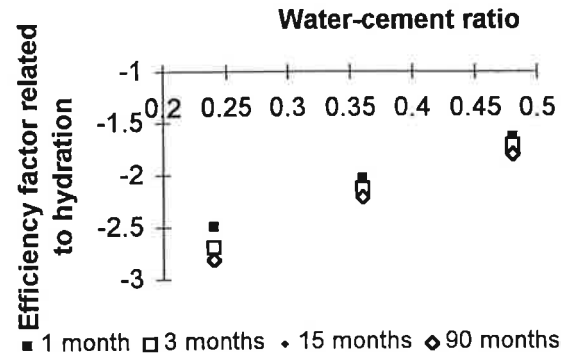


Figure 15 Efficiency factor of 10% silica fume related to hydration versus w/c.

Figure 16 shows the heat of hydration versus time obtained in the experiments, Persson (1992). The temperature rise was affected by w/c, addition of silica fume, s.f. and/or superplasticiser, s.p., Persson (1992) and cp. Figures 1-4 above. S.f. did not significantly affect the total heat shown in Figure 17. With the strength held constant, addition of 10% silica fume did not affect the maximum temperature rise (of great importance related to the risk of cracking), Figure 18. The following equation of the heat of hydration after 200 h, Q_{200} , was obtained (kJ/kg):

$$Q_{200} = 370 \cdot (w/c)^{0.37} \quad (8)$$

5 Conclusions

Based on tests of hydration, structures and strength on more than 1800 cores and based on 8 semi-adiabatic tests on the heat release of concrete, the following conclusions were drawn:

- 1) Initially the effect of silica fume was very high on both self-desiccation and strength.
- 2) The effect of 10% silica fume (estimated on the basis of concrete content) on self-desiccation decreased with w/c at 28 days' age (reversed effect at 450 days).
- 3) The efficiency factor of 10% silica fume on strength decreased with w/c and with age.
- 4) The effect of 10% silica fume on split tensile strength dropped after 28 days' age which may be an effect of the pronounced autogenous shrinkage that occurs in concrete with silica fume.
- 5) A negative efficiency factor of 10% silica fume related to hydration was obtained since the calcium hydroxide in the concrete was consumed by the pozzolanic reaction.
- 6) Combined with superplasticiser, silica fume retarded the hydration process substantially.
- 7) The total heat of hydration in the concrete increased with w/c.
- 8) At a constant strength level the temperature rise was the same, with and without silica fume.

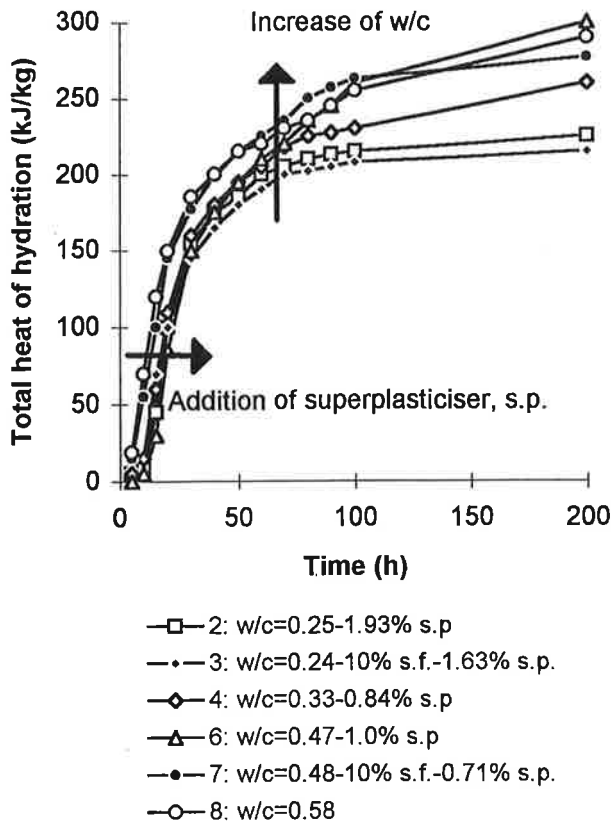


Figure 16 Heat of hydration versus time.

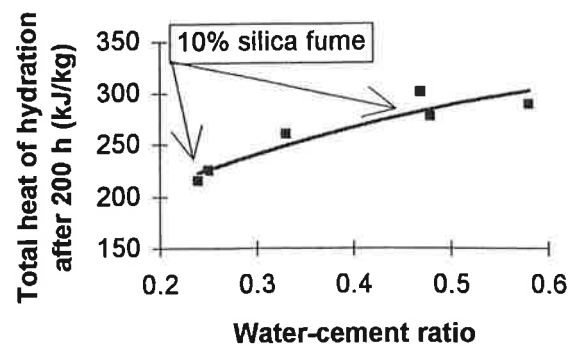


Figure 17 Heat of hydration versus w/c

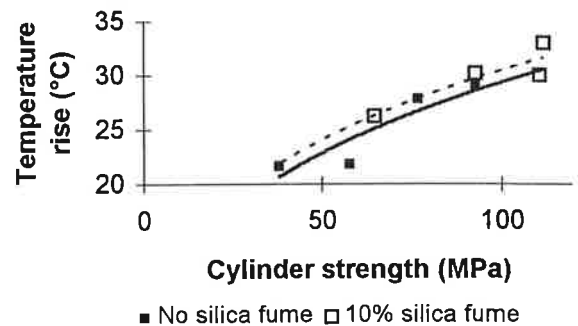


Figure 18 Maximum temperature rise.

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