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ABSTRACT

This article outlines an experimental and numerical study of the long-term interaction between silica fume and Portland cement in concrete subjected to air, water or sealed curing. 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 silica fume. Parallel studies of strength, 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 the years 1989 and 1996.

RÉSUMÉ

Cet article expose une étude expérimentale et numérique sur l'interaction à long terme de la fumée de silice et du ciment portland dans la béton exposé à l'influence de l'air, de l'eau ou dans un milieu de conservation hermétique. Dans ce but, prés de 2000 kg de béton de huit qualités de béton différentes ont été étudiés à 4 âges chacune sur une période de 90 mois. La moitié des bétons contenait de la fumée de silice. Des études parallèles ont été menées sur la résistance, l'hydratation et l'humidité relative interne. Des résultats nouveaux et originaux et des analyses y sont présentées sur l'interaction du ciment portland et de la fumée de silice ayant trait à la résistance au fendage par tension, l'hydratation et l'humidité relative interne. Ce projet a été réalisé entre 1989 et 1996.

1. BACKGROUND

In recent years silica fume has been used to obtain high strength, high fluidity and other high qualities in concrete. However, the efficiency factor of silica fume related to strength, hydration and self-desiccation has not been sufficiently analysed yet, particularly not with regard to the effect of time, t, and the water-cement ratio, w/c. Reports have been presented over the last few years dealing with the decrease of strength of concrete over time due to content of silica fume [1]. The decrease was related to the amount of micro-cracking that occurred in a concrete containing silica fume. Some of the observations have been explained by different moisture conditions in the concrete when the compressive tests were carried out [2]. 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 [3]. Finally the development of hydration differs substantially between concretes with and without silica fume [4]. During the pozzolanic interaction between silica fume and Portland cement some calcium-hydroxide was transformed into silicate-hydrates which decreased the degree of hydration but increased the strength. To complete the pozzolanic reaction between silica fume and Portland cement about 16% silica fume is required calculated on the basis of the cement content [5]:

$$3\ Ca(OH)_2 + 2\ SiO_2 = 3\ CaO.2\ SiO_2.3\ H_2O. \qquad (1)$$

Since no water was consumed during the pozzolanic reaction, no additional chemical shrinkage occurred [4]. The additional basic shrinkage was instead explained by the extended depression in the pore water when silica fume was used in the concrete [6].

2. OBJECTIVES OF THE WORK

The main objective of the work was to compare, over at least 6 years, the compressive strength and split tensile strength of mass concrete with 10% silica fume with the same properties of concrete without silica fume. The water-cement ratio was to vary between 0.2 and 0.6. Three different curing conditions were to be studied: sealed, air and water curing. The mass concrete was to be poured in a way that avoided influences of the pouring conditions on the specimens. Parallel studies were to be carried out on the internal relative humidity and on the development of hydration of the concretes.

3. EXPERIMENTAL

3.1 Specimen

Compressive strength, f_c, split tensile strength, f_{sp} and hydration were studied on cores, 80 mm long and 40 mm in diameter, drilled out of large concrete specimens (250 kg each). Half of the specimens contained silica fume. All other material parameters were held constant. The concrete was poured in the shape of a disc, 1 m in diameter and 0.1 m thick. To simulate a long column, the flat sides of the disc were sealed by thick layers of epoxy resin; at least 2 mm. Also the circular surface of one third of the specimens was sealed by a minimum of 2 mm epoxy resin. The diffusion of moisture through the epoxy resin was negligible compared to the diffusion through the porous concrete. One third of the specimens were subjected to a climate with a temperature varying between 18°C and 24°C and an ambient relative humidity between 23% and 48% [7]. The remaining third of the specimens were submerged and cured in water. A total of 1854 measurements were carried out, Table 1

3.2 Testing methods

A total of 936 cylinder cores were taken in equal shares at a distance of 50, 150 or 350 mm from the exposed surface in order to study strength and hydration. During the testing of strength interlayers of hardboard were used. A total of 642 ignition tests were carried out to obtain the hydration of the specimens [4,8]. Compensation was made for the ignition losses of cement and aggregate [4,8]. Cast-in plastic tubes were placed at different distances, 50, 150 and 350 mm, from the exposed circular surface of the column. Parallel to the cast-in items, thermo couples were placed in the concrete [7]. The measurement points were protected by a cover made of expanded plastic insulation in order to minimise the effects of variations in the ambient climate in the laboratory. The measurement period was 22 h. The probes were carefully calibrated [9].

4. STUDIED MATERIAL

Table 2 shows the chemical composition of the low-alkali cement used [4]. Eight types of concrete were studied in all 24 large concrete specimens. The aggregate consisted of crushed quartzite sandstone 8-12 mm (compressive strength: 333 MPa, split tensile strength: 15 MPa, Young's modulus: 60 GPa [10] and ignition losses: 0.25% [11]) together with natural gravel 0-8 mm (granite, ignition losses: 0.85% [11]. The silica fume was granulated powder (ignition losses: 2.25% [11]). The superplasticiser (naphthalene sulphonate) was added 30 s after all the other materials during the mixing (mixing time: 240 s). In Table 3 the composition (kg/m^3 dry material) of the concretes, the properties in fresh state and the compressive strength are stated [11].

Table 1 - Number of measurements (m= month).

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
Ø	72	72	-	72	18
Total	432	432	180	432	378

Table 2 - Chemical composition of the cement

Analysed properties (%):	
CaO	64.6
SiO_2	21.8
Al_2O_3	3.34
Fe_2O_3	4.39
MgO	0.84
K_2O	0.62
Na_2O	0.07
Alkali	0.48
SO_3	2.23
CO_2	0.14
Free CaO	1.13
Mineralogical properties (%):	
C_2S	22.5
C_3S	53.0
C_3A	1.42
C_4AF	13.4
Physical properties:	
Ignition losses	0.63%
Blaine	325 m^2/kg
Density	3180 kg/m^3

Table 3 - Composition (kg/m^3 dry material) and properties of the concretes [11].

Littera	1	2	3	4	5	6	7	8
Quartzite 8-12 mm	1358	1306	1306	1214	1158	1150	1153	1145
Gravel 0-8 mm	525	630	549	723	730	846	825	812
Cement, low-alkaline	484	456	476	400	389	303	298	299
Silica fume, granulated powder	48	-	48	-	39	-	30	-
Superplasticiser (dry material)	13.32	8.84	7.78	3.35	3.07	3.01	2.13	-
Density	2533	2513	2500	2469	2456	2441	2451	2424
Water-cement ratio	0.222	0.251	0.243	0.326	0.358	0.465	0.483	0.577
Aggregate content	0.712	0.738	0.753	0.746	0.731	0.712	0.731	0.700
Air content (%)	0.95	1.5	0.8	1.4	1.1	1.1	0.95	0.75
Workability (vebe)	29	34	13	25	12	9	12	15
1-month strength (cylinder, MPa)	111	93	112	77	93	58	65	38
3-months strength (cylinder, MPa)	128	104	128	91	100	70	76	45
15-months strength (cylinder, MPa)	142	121	139	105	104	78	81	51
90-months strength (cylinder, MPa)	139	121	131	106	106	74	79	49

5. COMPRESSIVE STRENGTH

Figs 1, 2 and 3 give the development of strength with sealed, air and water curing respectively. (Filled marks = 10% silica fume.) Fig. 4 shows the strength of all the cores studied. Fig. 5 shows the strength of cores with interlayers, f_c, during testing versus strength of cores without interlayers, f_{cc}. The following influence of inter-layers on the strength, f_c, compared to strength without interlayers, f_{cc}, was obtained (MPa):

$$f_c = 0.944 \cdot f_{cc} \quad (1)$$

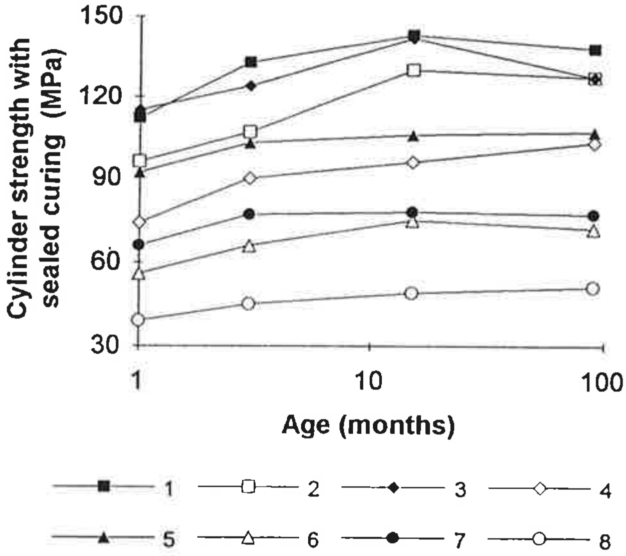


Fig. 1 - Strength versus age with sealed curing (mean value of 6 tests). Mix no. is given.

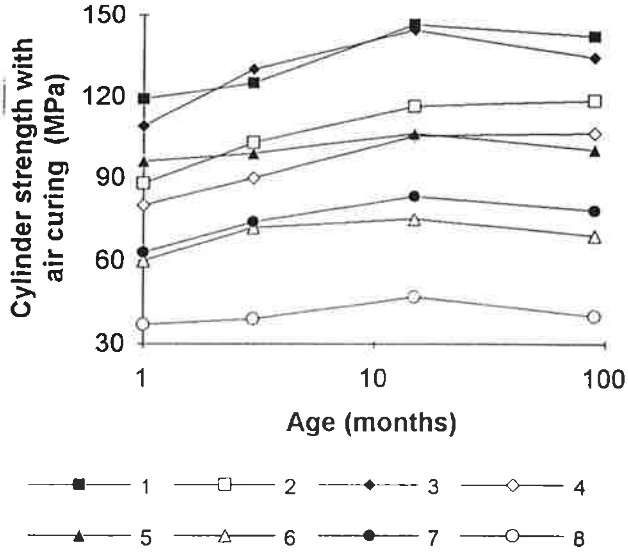


Fig. 2 - Strength versus age with air curing (mean value of 6 tests). Mix no. is given.

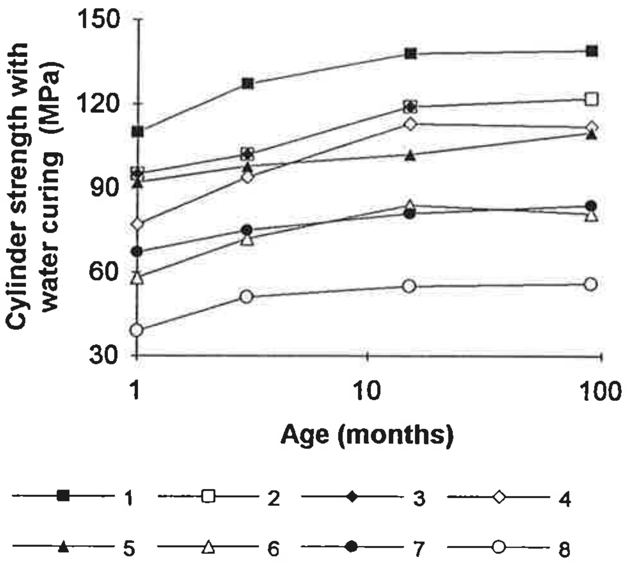


Fig. 3 - Strength versus age with water curing (mean value of 6 tests). Mix no. is given

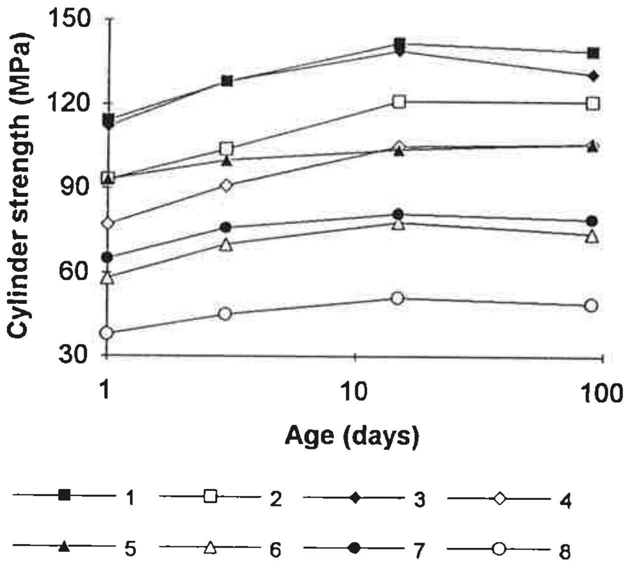


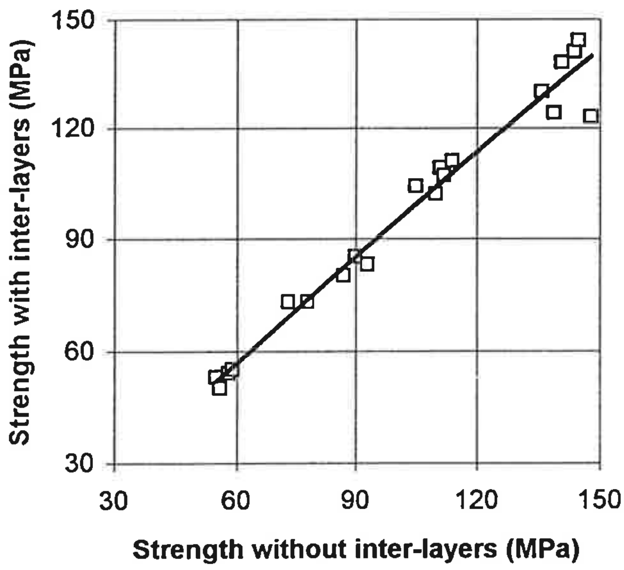
Fig. 4 - Strength versus age of all cores (mean value of 18 tests). Mix no. is given.

The moisture conditions in the core during the testing also had an influence on the result. Fig. 6 shows the strength at 5 months' age with 1 months of intensive drying of cores at 55°C, f_{cd}, and the strength with the mentioned drying period followed by water curing, f_{cw}, for another month. Fig. 6 refers to strength with sealed curing, f_c. The following equations were obtained:

$$f_{cd} = 1.194 \cdot f_c \tag{2}$$

$$f_{cw} = 0.866 \cdot f_c \tag{3}$$

Moisture stresses were avoided by studies with sealed conditions. Figs 7 to 10 show the strength as a function of the water-cement ratio for sealed, air, water and all three kinds of curing respectively (filled marks = 10% silica fume). The age is indicated (m= months).



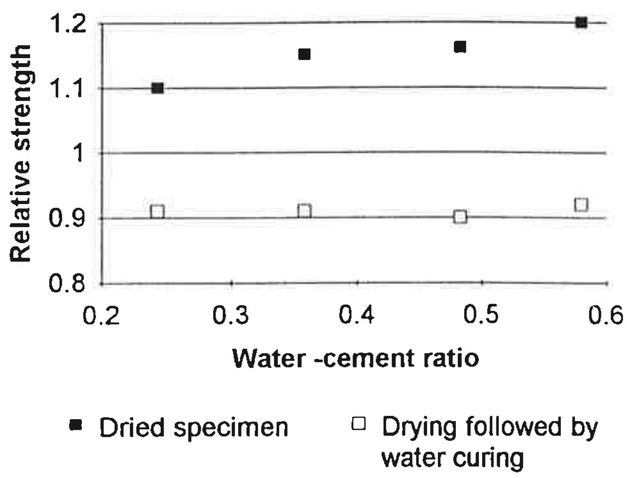
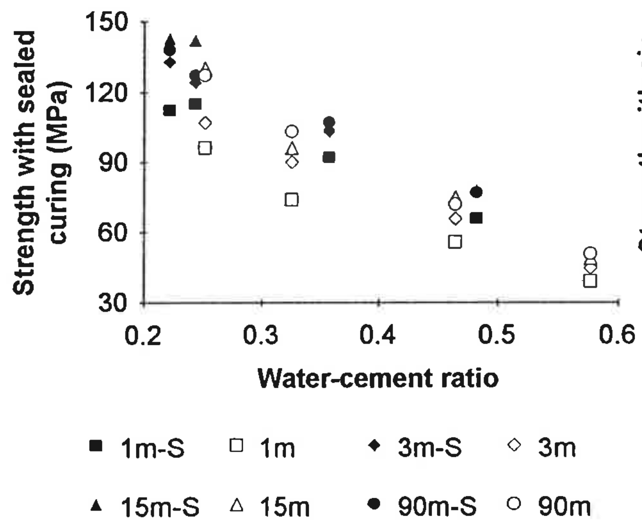


Fig. 5 - Strength of cores with interlayers, f_c, during testing versus strength of cores without inter-layers, f_{cc}.

Fig. 6 - Strength with intensive drying of cores, f_{cd}, and strength with drying followed by water curing, f_{cw}.



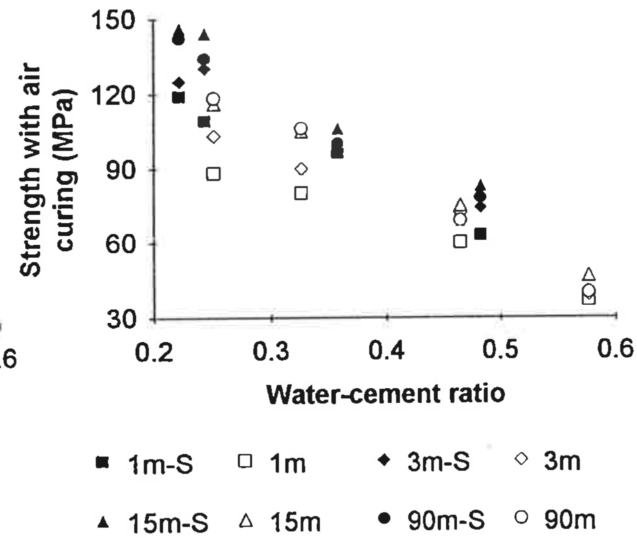


Fig. 7 - Strength versus water-cement ratio with sealed curing. m= months; S= 10% silica fume.

Fig. 8 - Strength versus water-cement ratio with air curing. m= months; S= 10% silica fume.

The following equation was used to describe the compressive strength (MPa):

$$f_c(w/c)=A\cdot(w/c)+B \quad (4)$$

$f_c(w/c)$ denotes the compressive strength (MPa)
w/c denotes the water-cement ratio
A, B are constants given in Table 4

The curing condition had a minor effect on the long-term strength. However, the influence of silica fume was more significant. At 1 months age concrete with 10% silica fume obtained about 15 MPa larger strength than concrete without silica fume (the water-cement ratio held constant). Based on equation (4) the time dependence of strength was found to be:

$$(\delta f_c/\delta t)_S \approx 10\cdot[0.7 - (w/c)]/t \qquad \{10\% \text{ silica fume}\} \qquad (5)$$

$$\delta f_c/\delta t \approx 15\cdot[0.73 - (w/c)]/t \qquad \{\text{No silica fume}\} \qquad (6)$$

t denotes age (months)
w/c denotes the water-cement ratio
$(\delta f_c/\delta t)$ denotes the strength development of concrete without silica fume (MPa/month)
$\delta f_c/\delta t)_S$ denotes the strength development of concrete with 10% silica fume (MPa/month)

As an average the long-term development of strength rate was about 55% larger in concrete without silica fume than in concrete with 10% silica fume.

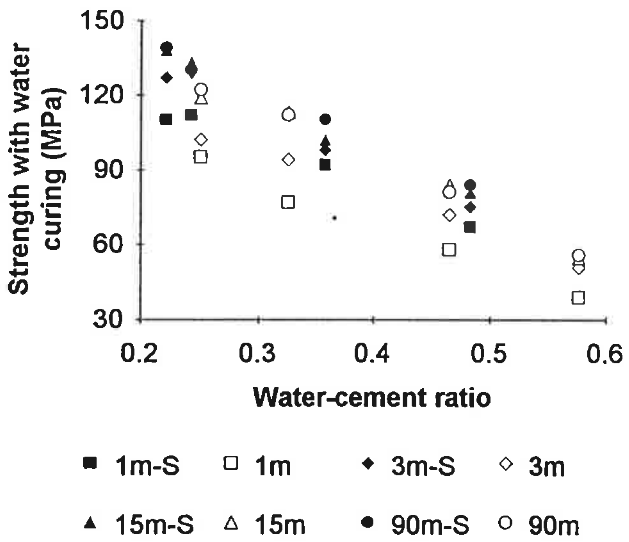


Fig. 9 - Compressive strength as a function of the water-cement ratio with water curing. m= months; S= 10% silica fume.

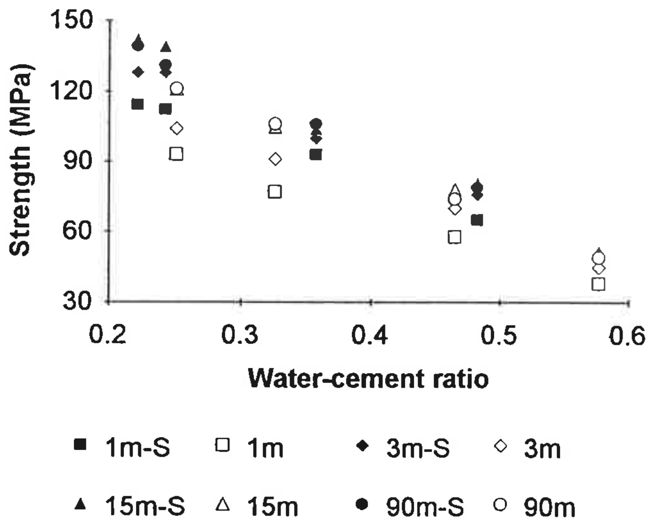


Fig. 10 - Compressive strength as a function of the water-cement ratio of all cores studied. m= months; S= 10% silica fume.

6. SPLIT TENSILE STRENGTH

Figs 11, 12 and 13 give the development of split tensile strength with sealed, air and water curing respectively. (Filled marks = 10% silica fume.) Fig. 14 shows the split tensile with sealed curing versus w/c. The following equation was used to describe the split tensile strength versus w/c:

$$f_{sp}(w/c)=C\cdot(w/c)+D \qquad (7)$$

$f_{sp}(w/c)$ denotes the split tensile strength (MPa)
w/c denotes the water-cement ratio
C, D are constants given in Table 4

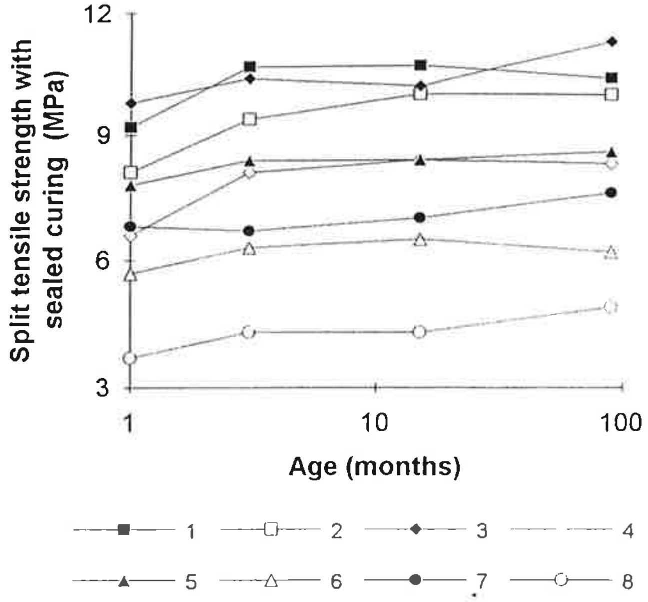


Fig. 11 - Split tensile strength versus age with sealed curing (mean value of 3 tests). Mix no. is given.

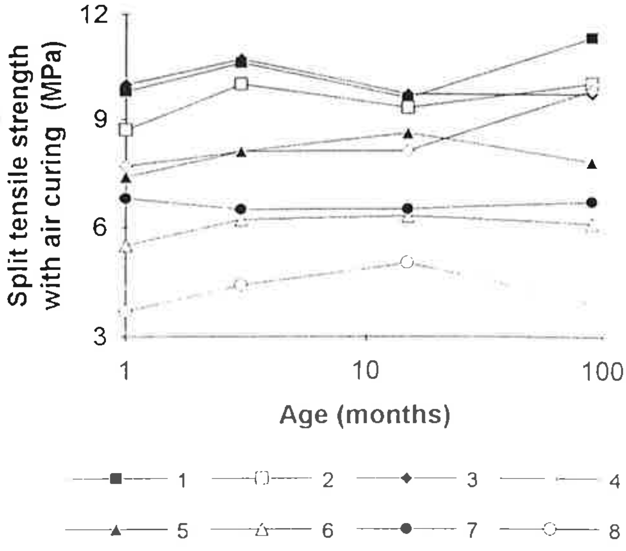


Fig. 12 - Split tensile strength versus age with air curing (mean value of 3 tests). Mix no. is given.

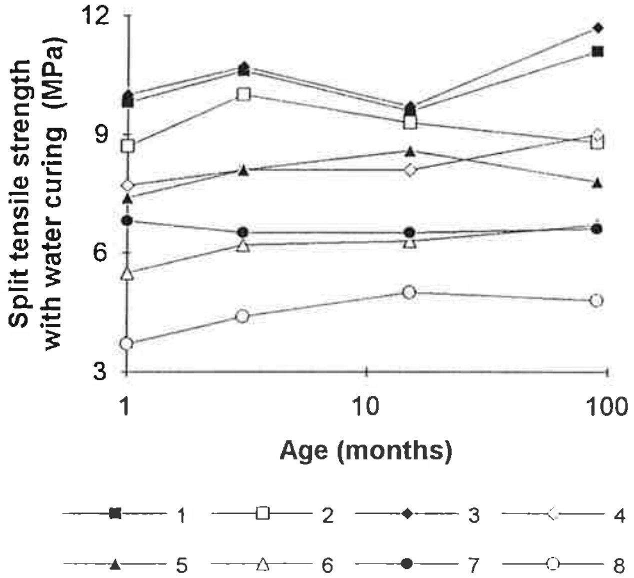


Fig. 13 - Split tensile strength versus age with water curing (mean value of 3 tests).

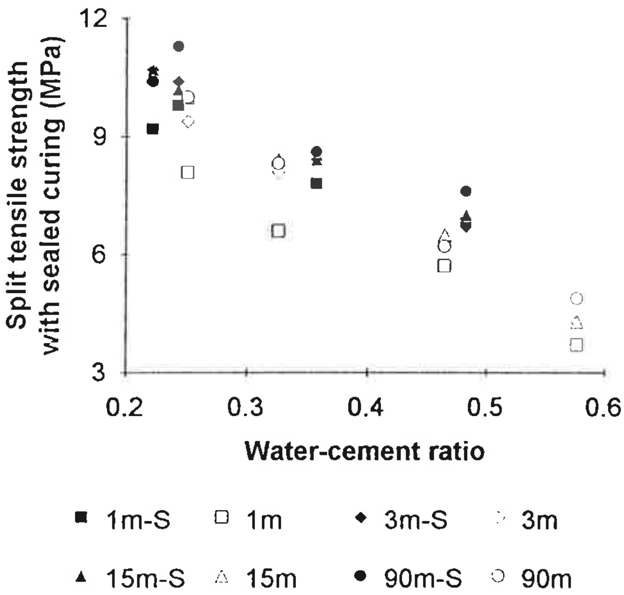


Fig. 14 - Split tensile strength versus age with all kinds of curing (mean value of 9 tests).

Table 4 - Constants of equations (4) and (5) (MPa)

Age (months)	Silica fume	A	B	C	D
1	10%	-186.26	167.06	-10.831	11.936
1	-	-166.23	133.53	-12.423	11.053
3	10%	-206.5	176.67	-15.524	14.119
3	-	-187.06	152.71	-15.25	13.197
15	10%	-259.46	201.96	-14.057	13.665
15	-	-231.05	181.02	-16.894	14.138
90	10%	-221.42	184.54	-13.142	13.766
90	-	-229.88	181.29	-15.419	13.591

7. HYDRATION

Figs 15, 16 and 17 give the development of hydration (non-evaporable water to cement) with sealed, air and water curing respectively. (Filled marks = 10% silica fume.) Fig. 18 shows the hydration of all the cores studied.

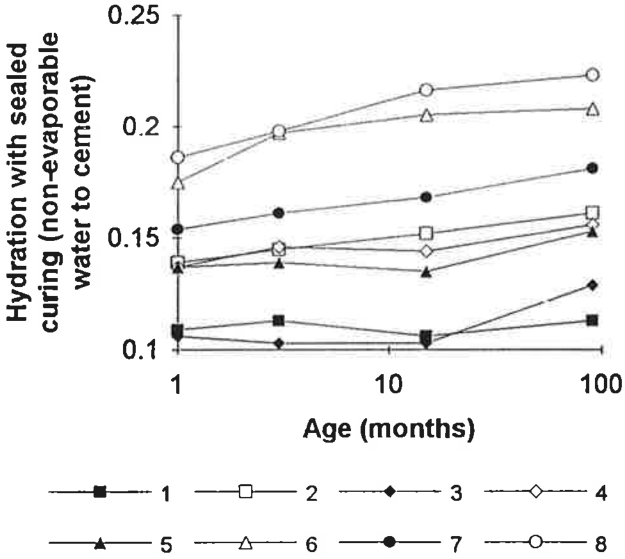


Fig. 15 - Hydration versus age with sealed curing (mean value of 6 tests). Mix no. is given.

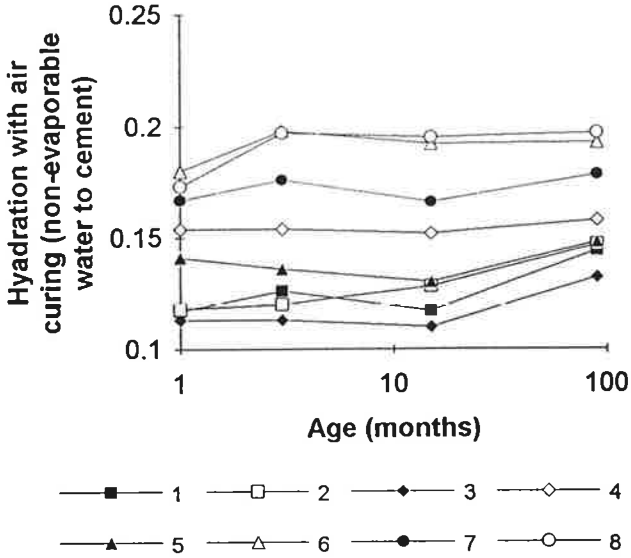


Fig. 16 - Hydration) versus age with air curing (mean value of 6 tests). Mix no. is given.

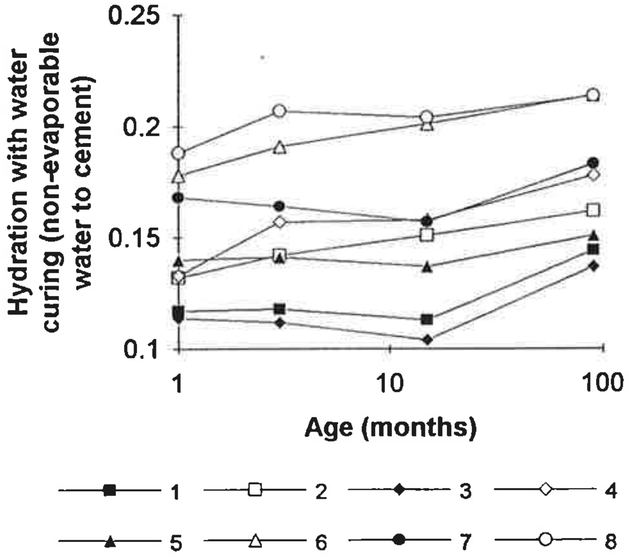


Fig. 17 - Hydration (non-evaporable water to cement) versus age with water curing (mean value of 6 tests). Mix no. is given.

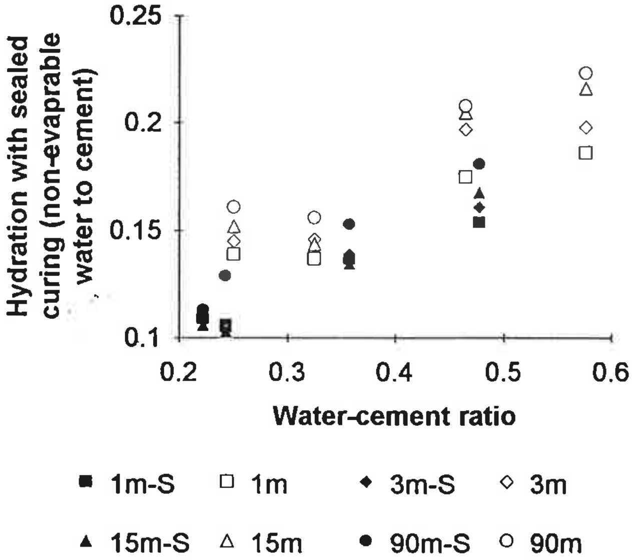


Fig. 18 - Hydration versus water-cement ratio independent of kind of curing (mean value of 18 tests). Mix no. is given.

The maximum degree of hydration, $\alpha = 1$, can only be obtained with a water-cement ratio, w/c, larger than 0.39 [12]. The maximum degree of hydration, α_{max}, of concrete with w/c<0.39 is linearly dependent on the water-cement ratio, w/c [11]:

$$\alpha_{max} = \frac{w}{0.39 \cdot c} \tag{8}$$

The degree of hydration, α, can also be expressed as:

$$\alpha = \frac{w_n}{0.25 \cdot c} \tag{9}$$

c denotes the cement content in the concrete (kg/m^3)
w denotes the water content in the concrete (kg/m^3)
w_n denotes the non-evaporable water content of the concrete (kg/m^3)

Dividing equation (8) by equation (9) gave the maximum value of the relative hydration:

$$(w_n/w)_{max} = 0.64 \qquad \{0<w/C<0.39\} \tag{10}$$

$$(w_n/w)_{max} = 0.25 \cdot c/w \qquad \{w/C>0.39\} \tag{11}$$

In Fig. 19 the relative hydration (non-evaporable water to mixing water) in concrete with sealed curing is given as a function of the water-cement ratio. Fig. 19 gave a equation of the development of the relative hydration with sealed curing as a function of the water-cement ratio:

$$(w_n/w)_S\,(t,w/c) = 0.0113 \cdot [\ln(t) + 20)] \cdot (w/c)^{0.006 \cdot t \cdot (1-0.01 \cdot t)-0.5} \qquad \{10\% \text{ silica fume}\} \tag{12}$$

$$(w_n/w)\,(t,w/c) = 0.0117 \cdot [\ln(t) + 20)] \cdot (w/c)^{0.006 \cdot t \cdot (1-0.01 \cdot t)-0.6} \qquad \{\text{No silica fume}\} \tag{13}$$

ln(t) denotes the natural logarithm of age, t, in months
w/c denotes the water-cement ratio

8. INTERNAL RELATIVE HUMIDITY

The internal relative humidity, Ø, of the concrete was of great importance in explaining the development of hydration [13]. However, after 15 months the measurement programme on Ø was limited due to leakage through or missing rubber plugs on the plastic tubes used. The 90-months measurements of Ø with sealed curing were only carried out on concretes that were kept in glass flasks. Figs 20, 21 and 22 give the development of Ø with sealed, air and water curing respectively. (Filled marks = 10% silica fume.) Fig. 23 gives Ø versus w/c. From Fig. 23 two different equations of Ø (with or without silica fume) were obtained related to age and w/c [7]:

$$\text{Ø}_S(t,w/c) = 1.13 \cdot [1-0.065 \cdot \ln(t)] \cdot (w/c)^{0.24 \cdot [1-0.1 \cdot \ln(t)]} \qquad \{1<t<15 \text{ months}; 0.2<w/c<0.6\} \tag{14}$$

$$\text{Ø}(t,w/c) = 1.09 \cdot (w/c)^{0.17 \cdot (1+0.0451 \cdot t)} \qquad \{1<t<15 \text{ months}; 0.2<w/c<0.6\} \tag{15}$$

ln(t) denotes the natural logarithm of age, t, in months
S denotes 10% silica fume

After 15 months' age Ø remained more or less constant with sealed curing according to the few measurements that were available, Fig. 21.

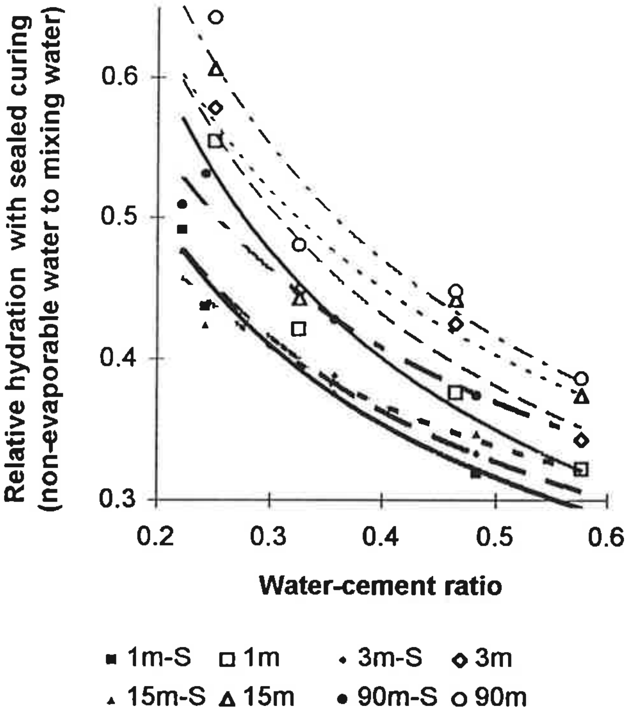


Fig. 19 - Relative hydration (non-evaporable water to mixing water) in concrete with sealed curing. m= months; S= 10% silica fume

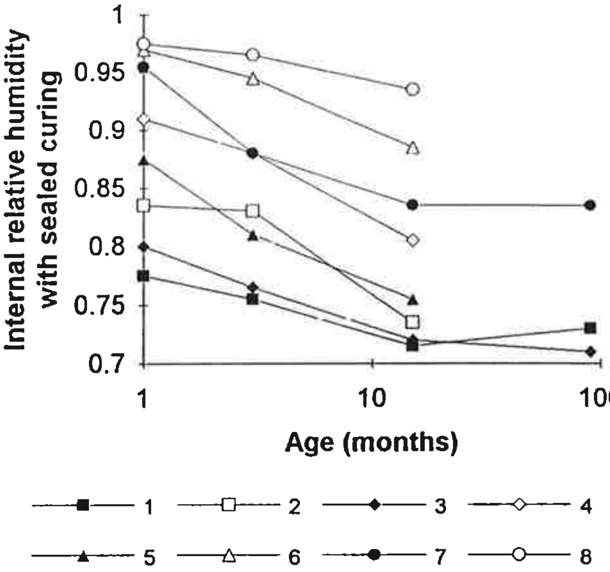


Fig. 20 - Internal relative humidity with sealed curing (mean value of 6 measurements). Mix no. is given (Table 3).

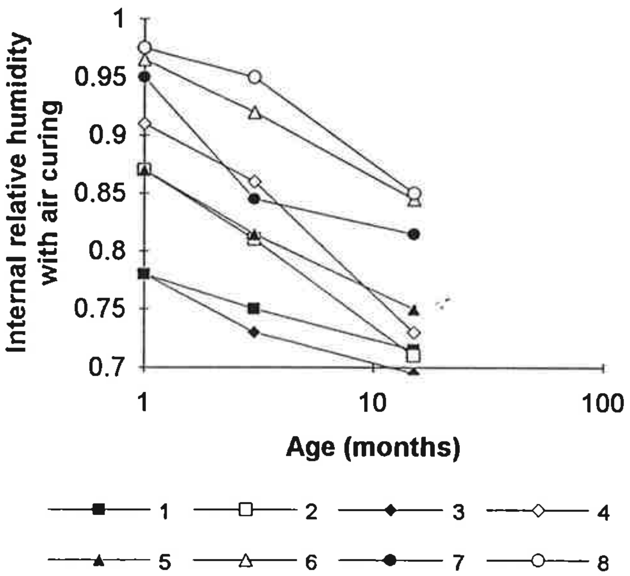


Fig. 21 - Internal relative humidity 50 mm from the exposed surface with air curing (mean value of 2 measurements). Mix no. is given (Table 3).

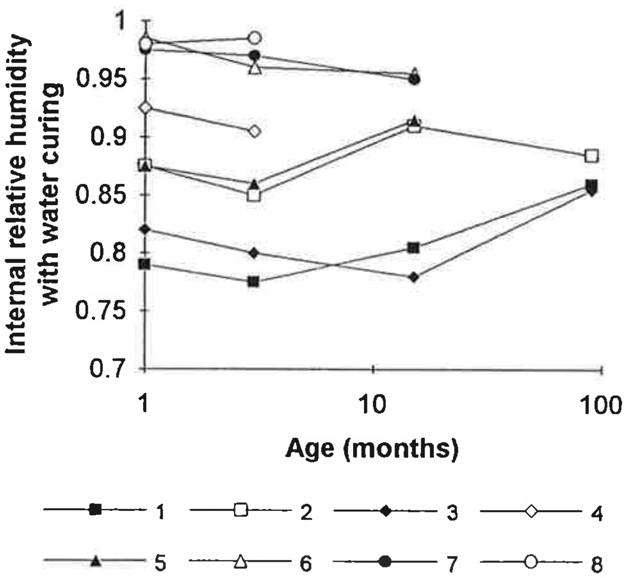


Fig. 22 - Internal relative humidity 50 mm from the exposed surface with water curing (mean value of 2 measurements). Mix no. is given (Table 3).

9. ACCURACY

Tables 5, 6, 7 and 8 give the coefficient of variation of the measurements related to compressive strength, split tensile strength, hydration and internal relative humidity with sealed curing respectively. The coefficient of variation, χ, was defined according to the following equation:

$$\chi=\xi/m.v \qquad (16)$$

χ denotes the coefficient of variation
ξ denotes the standard deviation
m.v. denotes the mean value

Table 5 - Coefficient of variation related to compressive strength with sealed curing

Age/ concrete	1 m	3 m	15 m	90 m	m.v.
1	0.092	0.032	0.029	0.035	0.047
2	0.040	0.046	0.041	0.042	0.042
3	0.021	0.046	0.042	0.050	0.040
4	0.036	0.037	0.041	0.096	0.053
5	0.119	0.042	0.030	0.029	0.058
6	0.047	0.073	0.052	0.029	0.050
7	0.090	0.057	0.100	0.115	0.093
8	0.098	0.106	0.098	0.117	0.105
m.v.	0.069	0.055	0.054	0.065	0.061

m.v.= mean value

Table 6 - Coefficient of variation related to split tensile strength with sealed curing

Age/ concrete	1 m	3 m	15 m	90 m	m.v.
1	0.060	0.068	0.053	0.177	0.090
2	0.057	0.033	0.047	0.067	0.051
3	0.012	0.034	0.049	0.041	0.034
4	0.084	0.037	0.036	0.018	0.044
5	0.030	0.018	0.036	0.040	0.031
6	0.035	0.033	0.081	0.145	0.074
7	0.043	0.046	0.041	0.112	0.061
8	0.016	0.024	0.098	0.109	0.062
m.v.	0.042	0.037	0.055	0.089	0.056

m.v.= mean value

Table 7 - Coefficient of variation related to hydration with sealed curing

Age/ concrete	1 m	3 m	15 m	90 m	m.v.
1	0.032	0.037	0.036	0.041	0.036
2	0.020	0.035	0.072	0.027	0.039
3	0.073	0.052	0.118	0.024	0.067
4	0.044	0.045	0.024	0.038	0.038
5	0.068	0.051	0.030	0.032	0.045
6	0.028	0.038	0.030	0.051	0.037
7	0.035	0.041	0.065	0.022	0.041
8	0.052	0.054	0.066	0.046	0.054
m.v.	0.044	0.042	0.055	0.035	0.044

m.v.= mean value

Table 8 - Coefficient of variation related to internal relative humidity with sealed curing

Age/ concrete	1 m	3 m	15 m	90 m	m.v.
1	0.021	0.017	0.020	0.068	0.032
2	0.004	0.012	0.037	-	0.018
3	0.018	0.02	0.038	0.046	0.031
4	0.023	0.016	0.046	-	0.028
5	0.021	0.019	0.057	-	0.032
6	0.008	0.013	0.026	-	0.016
7	0.008	0.022	0.043	0.006	0.020
8	0.003	0.007	0.020	-	0.010
m.v.	0.013	0.016	0.036	0.040	0.023

m.v.= mean value

The measurements related to both compressive and split tensile strength on concretes with low water-cement ratio, w/c< 0.39, obtained a variation coefficient around or less than 5% which was acceptable since drilled cores were studied. However, measurement of normal concretes with w/c$\geq$ 0.39 had a slightly larger variation coefficient. The reason for this rise in the variation coefficient was not known. Especially when related to the measurements of split strength, the coefficient of variation increased with the age, which may also be an effect of basic shrinkage that continuously extended in concretes due to self-desiccation [3]. Measurements of hydration and internal relative humidity exhibited low coefficients of variation, 4.4% and 2.3% respectively.

10. ANALYSIS AND DISCUSSION

10.1 General

The pozzolanic effect of silica fume, k, was defined according to the following equation:

$$(w/c)_{eff} = w/(c+k\cdot s) \quad (17)$$

c denotes the cement content (kg/m^3)
k denotes the efficiency factor of silica fume
s denotes the content of silica fume (=10% of the cement content for mixed proportions 1, 3, 5 and 7, Table 3)
w denotes all the mixing water (kg/m^3)
$(w/c)_{eff}$ denotes the efficient (eff) water-cement ratio, i.e. the water-cement ratio that was used in concrete without silica fume in order to obtain identical properties (compressive strength, split tensile strength, hydration or internal relative humidity) to concrete with 10% silica fume, with the water-cement ratio held constant.

The definition of the efficiency factor of silica fume, k, could be discussed. About 60% of the amount of silica fume (10% calculated on the basis of the cement content) was available for the reaction with Portland cement to come to an end given a degree of hydration, $\alpha=1$ [5]. After 90 months of hydration the ratio of the non-evaporable water to cement, w_n/c, in concretes without silica fume varied between 0.16 and 0.22, i.e. less than 0.25. The ratio of non-evaporable water to cement, $w_n/c \approx 0.25$, was required for the reaction between water and cement to come to an end. However, until 15 months' age, w_n/c was less than $0.6\cdot 0.25 = 0.15$ for concretes with $w/c < 0.39$, which theoretically implied that a sufficient amount of silica fume still remained in concretes with $w/c < 0.39$ for the long-term interaction between Portland cement and silica fume to continue.

For concretes with $w/c \geq 0.39$ the pozzolanic reaction between Portland cement and silica fume took place mainly before 1 month's age but for concretes with $w/c < 0.39$ the pozzolanic interaction was still observed during the studies at 15 months' age. From the practical point of view it was essential to use an amount of silica fume in the concrete that did not exceed the present limitations in the national regulations, 10% of the cement content, even though from the theoretical point of view it would have been of interest to study concrete with more silica fume than 16% [5]. The main objective of the work, however, was to compare properties of mass concrete with 10% silica fume with the same properties of concrete without silica fume

10.2 Internal relative humidity

The internal relative humidity, Ø, was of the utmost importance for describing the hydration of the concrete. Reaction products, i.e. hydroxides, from the hydration were required for the pozzolanic reaction to take place [5]. When the internal relative humidity decreased the pozzolanic reaction also decreased and finally ceased [13]. Self-desiccation of concrete was also of great importance [3]. Basic (autogenous) shrinkage was more pronounced in concretes with silica fume than in concretes without silica fume. The basic (autogenous) shrinkage was clearly related to the self-desiccation [3] of the concrete. It was also observed that the self-desiccation was caused by depression in the pore water [6], also more expressed in concretes with silica fume. The basic shrinkage caused tensile stresses in the cement paste but compression in the aggregate of the concrete [6]. This was of great importance in explaining the mechanical properties of the concrete such as compressive strength and split tensile strength.

Due to the compression of the aggregate of the concrete with low w/c (which increased continuously due to the basic shrinkage) the total compressive capacity of the concrete decreased slightly in concretes of low w/c with silica fume. When the basic (autogenous) shrinkage exceeded the tensile strain of the cement paste, which often occurred in concretes with low w/c and containing silica fume [6], cracks occurred. The amount of cracking was clearly related to a decreasing compressive strength of the concrete [1].

To evaluate the efficiency factor related to self-desiccation, k_{sc}, the equations (14) and (15) above were used, i.e. w/c in equation (15) was replaced by $(w/c)_{eff}$ according to equation (17). After this replacement of w/c in equation (15) the equations (14) and (15) were equalised and the efficiency factor, k_{se}, easily calculated. Fig. 24 shows the efficiency factor related to self-desiccation. The efficiency factor, k_{sc}, was described by the following equation:

$$k_{sc}(t,w/c) = 2\cdot(t-8.33)\cdot(w/c)-0.77\cdot t+9.2 \qquad \{1<t<15 \text{ months}; 0.25<w/c<0.50\} \qquad (18)$$

t denotes the age of the concrete (months)
w/c denotes the water-cement ratio

At w/c ≈ 0.39, the efficiency factor, k_{se} =2.7 was observed fairly independent of age. However, at lower w/c, k_{se} was larger at 1 and 3 months' age and smaller at 15 months' age since the hydration then ceased and also the pozzolanic reaction. The contrary was observed at higher w/c where the hydration continued and obviously also the pozzolanic reaction in contrast to the relations stated in the general discussion above. The pozzolanic reaction caused smaller average pore diameter in the gel and thus lower Ø according to the well-known Kelvin equation [14].

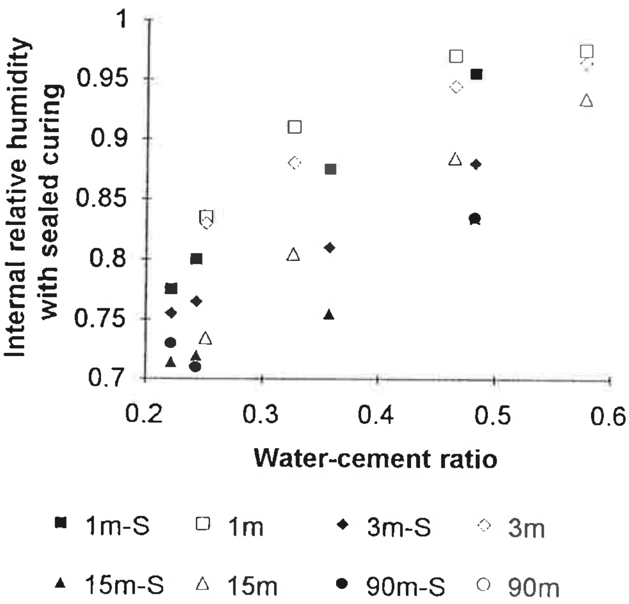


Fig. 23 - Internal relative humidity with sealed curing. m= months; S= 10% silica fume.

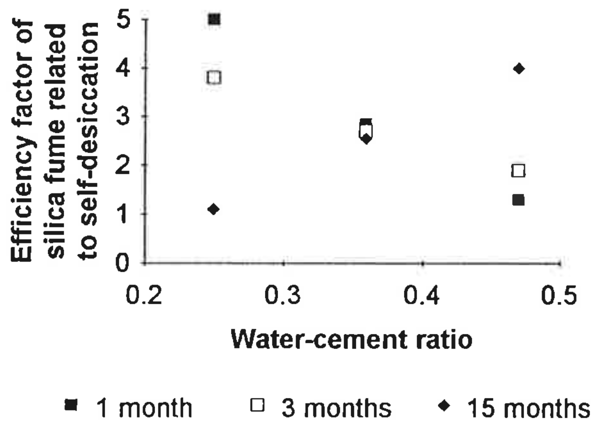


Fig. 24 - Efficiency factor of silica fume related to internal relative humidity with sealed curing (self-desiccation).

10.3 Compressive strength

Initially the effect of silica fume on the compressive strength was pronounced, especially in concrete with low w/c. The early pozzolanic reaction created reaction products such as calcium-silicate-hydrates instead of calcium-hydrates with about 15 MPa larger strength. However, due to the remarkable self-desiccation in concretes with silica fume, especially in concretes with low w/c, the hydration ceased and thus the hydration, the pozzolanic reaction and finally also the increase of strength, cp. equations (5) and (6) above. The rate of long-term strength was about 55% larger in concretes without silica fume than in concretes with 10% silica fume. Only sealed curing was studied regarding the efficiency factor related to strength, k_{sc}. To evaluate the efficiency factor the equation (4) was used i.e. w/c in the equation valid for concrete without silica fume was replaced by $(w/c)_{eff}$ according to equation (17). After this replacement of w/c in equation (4) the equations valid for concrete with and without silica fume were equalised and the efficiency factor, k_{sc} estimated. Fig. 25 shows the efficiency factor related to compressive strength described by the following equation:

$$k_{sc}(t,w/c) = 0.113\cdot[4.44-\ln(t)]\cdot(w/c)^{-0.056\cdot[\ln(t)+35]} \qquad \{1<t<90 \text{ months}; 0.25<w/c<0.50\} \qquad (19)$$

ln(t) denotes the natural logarithm of the age of the concrete, t (months)
w/c denotes the water-cement ratio

10.4 Split tensile strength

Only sealed curing was studied regarding the efficiency factor related to split tensile strength, k_{sp}. To evaluate the efficiency factor, the equation (7) was used i.e. w/c in the equation valid for concrete without silica fume was replaced by $(w/c)_{eff}$ according to equation (16). After this replacement of w/c in equation (7) the equations valid for concrete with and without silica fume were equalised and the efficiency factor, k_{sp}, estimated. Fig 26 shows the efficiency factor related to split tensile strength, k_{sp}, described by the following equations:

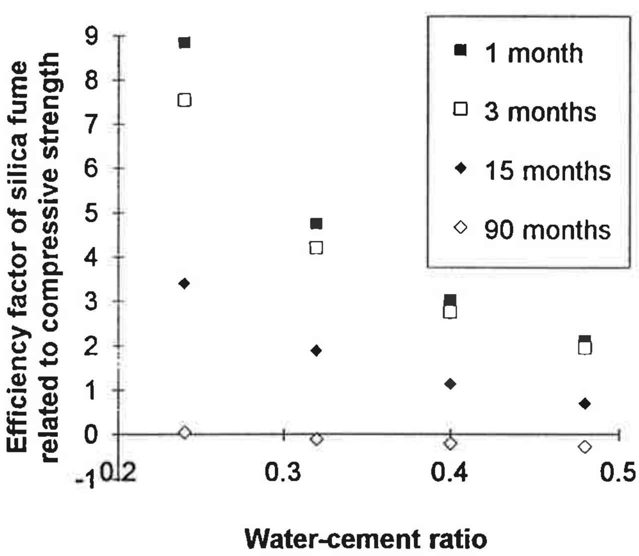


Fig. 25 - Efficiency factor of silica fume related to compressive strength. Sealed curing.

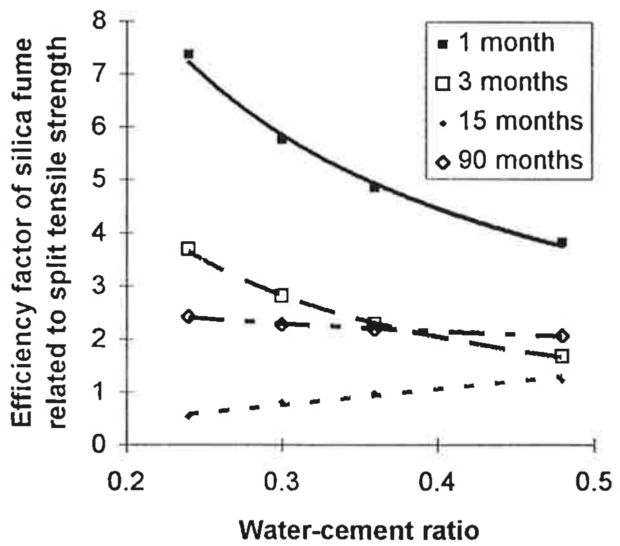


Fig. 26 - Efficiency factor of silica fume related to split tensile strength with sealed curing.

$k_{sp}(t,w/c) = 0.58\cdot(4.3-t)\cdot(w/c)^{-0.095\cdot(9+t)}$ {1<t<3 months; 0.25<w/c<0.50} (20)

$k_{sp}(t,w/c) = 0.018\cdot(185-t)\cdot(w/c)^{0.019\cdot(76-t)}$ {15<t<90 months; 0.25<w/c<0.50} (21)

ln(t) denotes the natural logarithm of the age of the concrete, t (months)
w/c denotes the water-cement ratio

Between 3 months' age and 15 months' age a substantial decrease of k_{sp} was observed, probably due to the pronounced basic shrinkage and micro-cracking that occurred in concretes with silica fume [1]; cp. the general discussion of the importance of self-desiccation above. Thus the factor k_{sp} was expressed by two equations due to the discontinuous behaviour after 3 months' age.

10.5 Split tensile strength and compressive strength

The ratio between compressive strength and split tensile strength became lower with higher strength [4]. One explanation for this observation was the limitations due to the split tensile strength of the aggregate ($f_{sp,max} \approx 0.75\cdot 15 = 12$ MPa). Another possible explanation for the development of the ratio between compressive and tensile strength was the pozzolanic interaction between Portland cement and silica fume. Silica fume was often used in concrete with higher strength. As mentioned above, the pozzolanic effect of silica fume caused micro-cracking in the cement paste and thus lower tensile strength in comparison to the compressive strength. Fig. 27 shows the split tensile strength as a function of the compressive strength for a total of 864 specimens. The relationship between split tensile strength decreased both with higher strength and with age in concretes with 10% silica fume compared to concretes without silica fume. The following equations were obtained :

$f_{sp,s} = [0.281-0.0144\cdot\ln(t)]\cdot(f_c)^{0.744+0.0109\cdot\ln(t)}$ {30< f_c <150 Mpa; 1<t<90 } (22)

$f_{sp} = [0.144+0.0084\cdot\ln(t)]\cdot(f_c)^{0.902-0.0165\cdot\ln(t)}$ {30< f_c <150 MPa; 1<t<90 } (23)

f_c denotes the compressive strength (MPa)
f_{sp} denotes the split tensile strength (MPa)
ln (t) denotes the natural logarithm of age, t (months)
s denotes 10% calculated on the basis of the cement content
w/c denotes the water-cement ratio

10.6 Hydration

Only sealed curing was studied regarding the efficiency factor, k_{wn}, related to the relative hydration, w_n/w. To evaluate the efficiency factor the equations (12) and (13) were used, i.e. w/c in the equation (13) valid for concrete without silica fume was replaced by $(w/c)_{eff}$ according to equation (17). After this replacement of w/c in equation (13) the equations valid for concrete with and without silica fume, (12) and (13) respectively, were equalised and the efficiency factor, k_{sc} estimated. Fig. 28 shows the efficiency factor, k_{wn}, related to the relative hydration, w_n/w, described by the following equation {1<t<90 months; 0.25<w/c<0.50}:

$k_{wn}(t,w/c) = 0.043\cdot(\ln(t)+30)\cdot\ln(w/c) - 0.006\cdot t\cdot(1-0.01\cdot t) - 0.71$ (24)

ln(t) denotes the natural logarithm of the age of the concrete, t (months)
ln(w/c) denotes the natural logarithm of the age of the water-cement ratio, w/c

10.7 Hydration and compressive strength

The interaction of Portland cement and silica fume clearly affected the relationship between relative hydration, w_n/w, and strength, Fig. 29. In concrete with 10% silica fume the maximum strength was obtained at $w_n/w \approx 0.45$ but at $w_n/w \approx 0.60$ in concrete without silica fume.

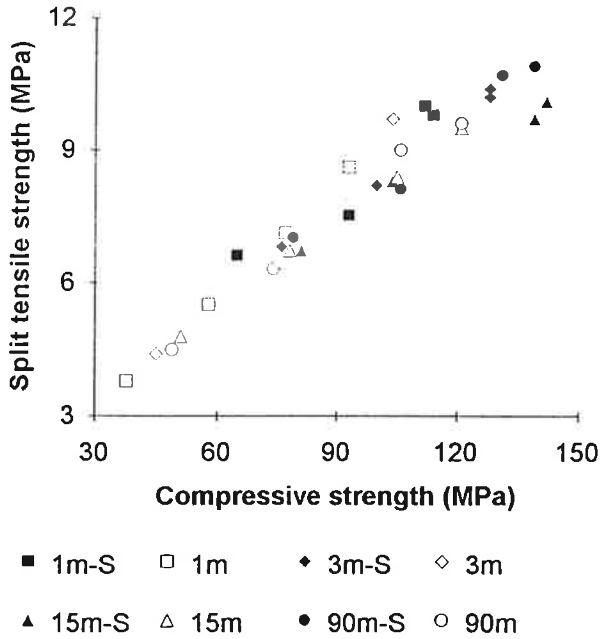


Fig. 27 - Split tensile strength versus the compressive strength in concrete with different age. m= months; S= 10% silica fume.

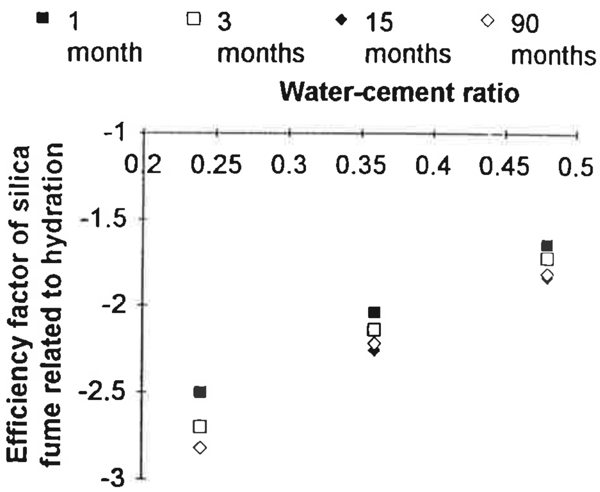


Fig. 28 - Efficiency factor of silica fume related to the relative hydration versus the water-cement ratio. Sealed curing.

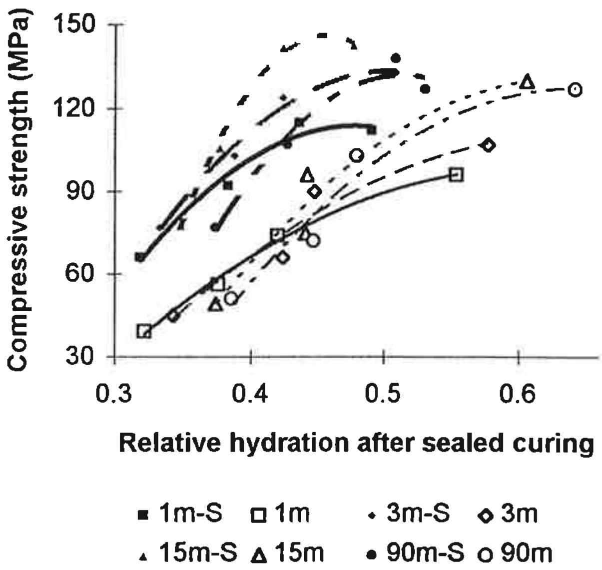


Fig. 29 - Compressive strength as a function of relative hydration, w_n/w. Sealed curing.

11. CONCLUSIONS

Large concrete specimens, about 2000 kg of concrete, were used in long-terms studies of the effect of silica fume on the properties of concrete related to strength, hydration and internal relative humidity. Half of the concretes contained 10% silica fume calculated in relation to the cement content. More than 900 cores were studied to determine their strength. More than 1800 observations were carried out over 90 months. The following conclusions were drawn:

1. Initially, within 3 month's age, silica fume had a positive effect on all the studied properties of concrete (compressive and split tensile strength and internal relative humidity) with the exception for hydration. The effect was pronounced on concretes with low water-cement ratio, w/c. The silica fume had larger effect on compressive and split tensile strength and internal relative humidity than cement. The so-called efficiency factor varied between 1 and 9 with the exception of the effect on hydration which varied between - 2.5 and -1.7.

2. Due to the low degree of hydration in concretes with low w/c< 0.39, silica fume still remained available for the pozzolanic interaction with the Portland cement, at least until 15 months' age. In concrete with higher w/c the pozzolanic effect stopped before 1 month's age due to the insufficient amount of silica fume available in the mix proportions.

3. After long, 90 months, the effect of silica fume on the strength development was negligible. Between 15 months' age and 90 months' age the efficiency factor of silica fume related to compressive strength became slightly negative compared to cement. This phenomen was most probably explained by the pronounced self-desiccation which consequently stopped the hydration in concretes with low w/c. In concretes with higher w/c no more silica fume remained for the pozzolanic interaction to continue after 1 months' age.

4. The pozzolanic interaction between silica fume and Portland cement also affected the basic shrinkage of the concrete, which most probably was the explanation for the unfavourable development of the split tensile strength in concretes with silica fume compared to concretes without silica fume. The tensile strain was most probably exceeded in concretes with silica fume, causing early micro-cracking in the cement-paste.

5. As a consequence of the basic shrinkage in concrete of low w/c and with 10% silica in the mix proportions, the efficiency factor of silica fume related to split tensile strength declined to about 1 before 15 months' age. After 15 months' age a rise to about 2 of the efficiency factor related to split tensile strength was observed. The rise was probably due to healing effect of the hydration of the cement occurring after 15 months' age (after the pozzolanic reaction had stopped).

6. The decline of compressive strength that was observed after 90 months' age in concretes of low w/c with silica fume was non-significant (of the same magnitude as the standard deviation).

7. The relationship between hydration and strength was quite different in concretes with and without silica fume due to the pozzolanic interaction between Portland cement and silica fume. Hydration was an inconsistent parameter to describe the properties of concrete with silica fume.

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APPENDIX I

Estimations of the efficiency factor of silica fume related to compressive strength

Equation (4) - 1 month

$-186.26\cdot(w/c) + 157.06 = -166.23\cdot(w/c)\cdot 1/(1+0.1\cdot k_{sc}) + 133.53$

$$k_{sc} = 10\cdot\left(\frac{1}{1.12049 - \frac{0.14155\cdot c}{w}} - 1\right) \qquad \text{(A1)}$$

c	denotes the cement content in the concrete (kg/m^3)
k_{sc}	denotes the efficiency factor of silica fume related to strength
w	denotes the water content of the concrete (kg/m^3)

k(0.24)=8.84
k(0.32)=4.75
k(0.40)=3.04
k(0.48)=2.11

Equation (4) - 3 months

$-206.5\cdot(w/c) + 176.67 = -187.06\cdot(w/c)\cdot 1/(1+0.1\cdot k_{sc}) + 152.71$

$$k_{sc} = 10\cdot\left(\frac{1}{1.10392 - \frac{0.12808\cdot c}{w}} - 1\right) \qquad \text{(A2)}$$

c	denotes the cement content in the concrete (kg/m^3)
k_{sc}	denotes the efficiency factor of silica fume related to strength
w	denotes the water content of the concrete (kg/m^3)

k(0.24)=7.54
k(0.32)=4.20
k(0.40)=2.76
k(0.48)=1.95

Equation (4) - 15 months

$-259.46\cdot(w/c) + 201.96 = -231.05\cdot(w/c)\cdot 1/(1+0.1\cdot k_{sc}) + 181.02$

$$k_{sc} = 10\cdot\left(\frac{1}{1.12296 - \frac{0.09063\cdot c}{w}} - 1\right) \qquad \text{(A3)}$$

c	denotes the cement content in the concrete (kg/m^3)
k_{sc}	denotes the efficiency factor of silica fume related to strength
w	denotes the water content of the concrete (kg/m^3)

$k(0.24)=3.42$
$k(0.32)=1.90$
$k(0.40)=1.16$
$k(0.48)=0.705$

Equation (4) - 90 months

$-221.42\cdot(w/c) + 184.54=-229.88\cdot(w/c)\cdot 1/(1+0.1\cdot k_{sc})+181.29$

$$k_{sc} = 10 \cdot \left(\frac{1}{1.0595 - \frac{0.01555 \cdot c}{w}} - 1\right) \qquad (A4)$$

c denotes the cement content in the concrete (kg/m^3)
k_{sc} denotes the efficiency factor of silica fume related to strength
w denotes the water content of the concrete (kg/m^3)

$k(0.24)=0.051$
$k(0.32)=-0.108$
$k(0.40)=-0.202$
$k(0.48)=-0.265$

Estimations of the efficiency factor of silica fume related to split tensile strength

Equation (7) - 1 month

$-10.831\cdot(w/c) + 11.936=--12.423\cdot(w/c)\cdot 1/(1+0.1\cdot k_{sp})+11.053$

$$k_{sp} = 10 \cdot \left(\frac{1}{0.87185 - \frac{0.071077 \cdot c}{w}} - 1\right) \qquad (A5)$$

c denotes the cement content in the concrete (kg/m^3)
k_{sp} denotes the efficiency factor of silica fume related to split tensile strength
w denotes the water content of the concrete (kg/m^3)

$k(0.24)=7.37$
$k(0.30)=5.75$
$k(0.36)=4.83$
$k(0.48)=3.82$

Equation (7) - 3 months

$-15.524\cdot(w/c) + 14.119=-15.25\cdot(w/c)\cdot 1/(1+0.1\cdot k_{sp})+13.197$

$$k_{sp} = 10 \cdot \left(\frac{1}{0.98235 - \frac{0.060459 \cdot c}{w}} - 1\right) \qquad (A6)$$

c	denotes the cement content in the concrete (kg/m^3)
k_{sp}	denotes the efficiency factor of silica fume related to split tensile strength
w	denotes the water content of the concrete (kg/m^3)

k(0.24)=3.69
k(0.30)=2.81
k(0.36)=2.28
k(0.48)=1.68

Equation (7) - 15 months

-14.057·(w/c) + 13.665=-16.894·(w/c)·1/(1+0.1· k_{sp})+14.138

$$k_{sc} = 10 \cdot \left(\frac{1}{0.83207 - \frac{0.027998 \cdot c}{w}} - 1\right) \quad \text{(A7)}$$

c	denotes the cement content in the concrete (kg/m^3)
k_{sp}	denotes the efficiency factor of silica fume related to strength
w	denotes the water content of the concrete (kg/m^3)

k(0.24)=0.54
k(0.30)=0.81
k(0.36)=0.99
k(0.48)=1.23

Equation (7) - 90 months

-13.142·(w/c) + 13.766=-15-419·(w/c)·1/(1+0.1· k_{sp})+13.591

$$k_{sp} = 10 \cdot \left(\frac{1}{0.85233 - \frac{0.01135 \cdot c}{w}} - 1\right) \quad \text{(A8)}$$

c	denotes the cement content in the concrete (kg/m^3)
k_{sp}	denotes the efficiency factor of silica fume related to split tensile strength
w	denotes the water content of the concrete (kg/m^3)

k(0.24)=2.42
k(0.32)=2.28
k(0.40)=2.18
k(0.48)=2.07

APPENDIX II

Results of measurements of strength after 90 months (remaining results according to [11])

Content

Mix composition	Page
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4	27
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6	29
7	30
8	31

Symbols

f_3	Cylinder strength (MPa)
f_{SPL}	Split tensile strength (MPa)
A	Water curing
B	Air curing
Betongtyp	Composition
C	Sealed curing
Medelvärden för platta	Mean value of slab
Medelvärden för hela receptet	Mean value of the whole mix
Tryck- och spräckhållfasthet	Compressive and split tensile strength

Appendix II:1 - Composition no. 1 (former composition no. 9 in [11])

Tryck- och spräckhållfasthet
Betongtyp 9

		d (mm)	ℓ (mm)	Brottkraft (kN)	f_3 (MPa)	f_{SPL} (MPa)	$f_{3,\,medel}$
	5T1	39.48	79.42	165.30	135.0		
	5T2	39.47	79.67	172.94	141.3		138.2
	5S	39.45	80.64	60.71		12.1	
	15T1	39.54	79.57	160.16	130.4		
A	15T2	39.45	79.83	172.49	141.1		135.8
	15S	39.54	80.63	56.24		11.2	
	35T1	39.49	80.00	176.31	144.0		
	35T2	39.50	80.05	161.12	131.5		137.7
	35S	39.56	80.35	49.23		9.9	
				Medelvärden för platta A:		11.1	137.2
	5T1	39.60	79.54	158.02	128.3		
	5T2	39.59	80.61	167.61	136.2		132.2
	5S	39.62	80.48	54.75		10.9	
	15T1	39.62	79.80	166.25	134.8		
B	15T2	39.59	79.67	165.51	134.5		134.6
	15S	39.63	80.39	60.61		12.1	
	35T1	39.62	79.65	179.70	145.8		
	35T2	39.62	80.58	164.57	133.5		139.6
	35S	39.67	80.90	54.88		10.9	
				Medelvärden för platta B:		11.3	135.5
	5T1	39.60	80.18	168.38	136.7		
	5T2	39.55	79.75	167.42	136.3		136.5
	5S	39.68	80.69	45.91		9.1	
	15T1	39.58	80.30	175.70	142.8		
C	15T2	39.61	79.53	160.89	130.6		136.7
	15S	39.69	80.78	63.00		12.5	
	35T1	39.65	79.96	162.15	131.3		
	35T2	39.58	79.58	171.81	139.6		135.5
	35S	39.68	80.17	48.05		9.6	
				Medelvärden för platta C:		10.4	136.2
			Medelvärden för hela receptet:			10.9	136.3

Appendix II:2 - Composition no. 2 (former composition no. 7 in [11])

Tryck- och spräckhållfasthet
Betongtyp 7

		d (mm)	ℓ (mm)	Brottkraft (kN)	f_3 (MPa)	f_{SPL} (MPa)	$f_{3,\ medel}$
	5T1	39.48	80.23	150.67	123.1		
	5T2	39.51	80.01	144.89	118.2		120.6
	5S	39.46	80.45	39.81		8.0	
	15T1	39.54	79.05	141.15	115.0		
A	15T2	39.60	80.13	141.95	115.3		115.1
	15S	39.53	80.56	34.21		(6.8)	
	35T1	39.49	79.77	145.65	118.9		
	35T2	39.51	79.24	160.00	130.5		124.7
	35S	39.46	80.22	47.35		9.5	
				Medelvärden för platta A:		8.1	120.1
	5T1	39.64	80.58	125.18	101.4		
	5T2	39.64	80.00	116.10	94.1		97.8
	5S	39.63	80.66	50.42		10.0	
	15T1	39.67	79.94	155.83	126.1		
B	15T2	39.60	80.04	152.31	123.7		124.9
	15S	39.69	80.95	50.92		10.1	
	35T1	39.64	80.60	136.73	110.8		
	35T2	39.52	80.53	147.52	120.3		115.5
	35S	39.64	80.98	49.39		9.8	
				Medelvärden för platta B:		10.0	112.7
	5T1	39.60	80.04	148.24	120.4		
	5T2	39.60	80.12	146.80	119.2		119.8
	5S	39.60	80.81	50.92		10.1	
	15T1	39.60	79.91	162.47	131.9		
C	15T2	39.65	80.09	158.47	128.3		130.1
	15S	39.61	80.70	46.60		9.3	
	35T1	39.60	79.76	150.60	122.3		
	35T2	39.60	79.85	157.07	127.5		124.9
	35S	39.61	80.87	47.10		9.4	
				Medelvärden för platta C:		9.6	124.9
			Medelvärden för hela receptet:			9.2	119.3

Appendix II:2a - Composition no. 2 (former composition no. 7 in [11])

Tryck- och spräckhållfasthet

Betongtyp 7

Littera	d (mm)	l (mm)	Last (kN)
7a5s2	39.45	80.43	47.17
7a15s1	39.61	80.37	46.22
7a15s2	39.58	80.51	53.99
7a35s1	39.62	80.62	53.87
7a35s2	39.49	80.49	52.72

Appendix II:3 - Composition no. 3 (former composition no. 8 in [11])

Tryck- och spräckhållfasthet
Betongtyp 8

		d (mm)	ℓ (mm)	Brottkraft (kN)	f_3 (MPa)	f_{SPL} (MPa)	$f_{3,\ medel}$
	5T1	39.48	79.80	144.80	118.3		
	5T2	39.48	80.26	141.16	115.3		116.8
	5S	39.38	80.38	47.06		9.5	
	15T1	39.36	80.24	182.65	150.1		
A	15T2	39.35	80.39	149.08	122.6		136.3
	15S	39.18	80.72	59.33		11.9	
	35T1	39.50	80.47	173.06	141.2		
	35T2	39.48	80.17	146.44	119.6		130.4
	35S	39.49	80.70	58.44		11.7	
				Medelvärden för platta A:		11.0	127.9
	5T1	39.33	79.96	147.04	121.0		
	5T2	39.34	80.32	163.66	134.6		127.8
	5S	39.15	80.72	50.71		10.2	
	15T1	39.41	80.09	161.97	132.8		
B	15T2	39.35	80.35	170.12	139.9		136.3
	15S	39.45	81.07	48.36		9.6	
	35T1	39.41	79.74	160.90	131.9		
	35T2	39.40	79.80	161.93	132.8		132.4
	35S	39.49	80.57	46.92		9.4	
				Medelvärden för platta B:		9.7	132.2
	5T1	39.66	79.74	143.73	116.3		
	5T2	39.65	79.74	152.09	123.2		119.8
	5S	39.68	80.84	58.86		11.7	
	15T1	39.57	79.37	157.51	128.1		
C	15T2	39.65	80.51	166.58	134.9		131.5
	15S	39.72	80.01	53.88		10.8	
	35T1	39.54	79.85	153.18	124.7		
	35T2	39.56	79.92	152.84	124.3		124.5
	35S	39.60	81.04	57.67		11.4	
				Medelvärden för platta C:		11.3	125.3
			Medelvärden för hela receptet:			10.7	128.4

Appendix II:4 - Composition no. 4 (former composition no. 5 in [11])

Tryck- och spräckhållfasthet
Betongtyp 5

		d (mm)	ℓ (mm)	Brottkraft (kN)	f_3 (MPa)	f_{SPL} (MPa)	$f_{3,\ medel}$
	5T1	39.53	79.73	128.17	104.4		
	5T2	39.51	80.02	142.21	116.0		110.2
	5S	39.51	80.58	47.26		9.5	
	15T1	39.61	80.27	137.67	111.7		
A	15T2	39.59	79.91	131.98	107.2		109.5
	15S	39.52	80.60	40.25		8.0	
	35T1	39.60	80.18	134.61	109.3		
	35T2	39.50	79.18	132.25	107.9		108.6
	35S	39.58	80.89	47.49		9.4	
				Medelvärden för platta A:		9.0	109.4
	5T1	39.64	80.72	115.75	93.8		
	5T2	39.66	79.77	113.69	92.0		92.9
	5S	39.62	80.84	47.18		9.4	
	15T1	39.66	79.19	143.52	116.2		
B	15T2	39.63	80.12	140.36	113.8		115.0
	15S	39.61	80.55	49.59		9.9	
	35T1	39.67	79.98	125.00	101.1		
	35T2	39.73	80.25	133.87	108.0		104.6
	35S	39.57	81.00	50.46		10.0	
				Medelvärden för platta B:		9.8	104.2
	5T1	39.64	79.85	126.74	102.7		
	5T2	39.65	80.44	131.45	106.5		104.6
	5S	39.63	80.96	41.21		8.2	
	15T1	39.64	80.24	133.61	108.3		
C	15T2	39.64	80.04	121.32	98.3		103.3
	15S	39.66	80.86	42.90		8.5	
	35T1	39.64	80.88	133.70	108.3		
	35T2	39.65	80.96	101.81	82.5		95.4
	35S	39.63	80.98	42.11		8.4	
				Medelvärden för platta C:		8.3	101.1
			Medelvärden för hela receptet:			9.0	104.9

Appendix II:5 - Composition no. 5 (former composition no. 6 in [11])

Tryck- och spräckhållfasthet
Betongtyp 6

		d (mm)	ℓ (mm)	Brottkraft (kN)	f_3 (MPa)	f_{SPL} (MPa)	$f_{3, medel}$
	5T1	39.50	79.86	131.44	107.3		
	5T2	39.51	79.90	133.94	109.2		108.3
	5S	39.51	80.75	38.70		7.7	
	15T1	39.53	79.59	134.14	109.3		
A	15T2	39.50	79.78	135.65	110.7		110.0
	15S	39.55	80.86	42.53		8.5	
	35T1	39.53	79.76	115.65	94.2		
	35T2	39.54	80.09	145.15	118.2		106.2
	35S	39.52	80.51	35.90		7.2	
				Medelvärden för platta A:		7.8	108.2
	5T1	39.70	80.30	113.41	91.6		
	5T2	39.64	80.58	105.45	85.4		88.5
	5S	39.88	80.60	37.24		7.4	
	15T1	39.66	80.63	131.44	106.4		
B	15T2	39.68	80.48	120.07	97.1		101.7
	15S	39.67	81.19	39.00		7.7	
	35T1	39.72	80.70	135.93	109.7		
	35T2	39.75	80.50	122.65	98.8		104.3
	35S	39.73	80.84	42.36		8.4	
				Medelvärden för platta B:		7.8	98.2
	5T1	39.50	80.04	130.24	106.3		
	5T2	39.51	80.76	123.91	101.1		103.7
	5S	39.52	80.51	42.02		8.4	
	15T1	39.53	79.70	134.70	109.8		
C	15T2	39.53	80.53	128.52	104.7		107.2
	15S	39.50	80.56	44.90		9.0	
	35T1	39.55	80.26	126.69	103.1		
	35T2	39.55	76.77	130.32	106.1		104.6
	35S	39.48	81.26	42.58		8.4	
				Medelvärden för platta C:		8.6	105.2
			Medelvärden för hela receptet:			8.1	103.8

Appendix II:6 - Composition no. 6 (former composition no. 3 in [11])

Tryck- och spräckhållfasthet
Betongtyp 3

		d (mm)	ℓ (mm)	Brottkraft (kN)	f_3 (MPa)	f_{SPL} (MPa)	$f_{3,\,medel}$
	5T1	39.53	79.39	95.60	77.9		
	5T2	39.52	80.88	93.37	76.1		77.0
	5S	39.52	80.49	34.58		6.9	
	15T1	39.47	80.22	95.13	77.7		
A	15T2	39.53	80.02	95.76	78.0		77.9
	15S	39.50	80.54	34.52		6.9	
	35T1	39.50	80.36	99.95	81.6		
	35T2	39.53	80.04	99.71	81.2		81.4
	35S	39.56	80.91	32.07		6.4	
				Medelvärden för platta A:		6.7	78.8
	5T1	39.65	79.39	67.47	54.6		
	5T2	40.02	79.68	80.15	63.7		59.2
	5S	39.92	81.00	35.84		7.1	
	15T1	39.40	79.37	92.08	75.5		
B	15T2	39.42	80.14	80.33	65.8		70.7
	15S	39.35	80.42	25.40		5.1	
	35T1	39.37	79.93	89.41	73.4		
	35T2	39.37	80.17	88.20	72.5		72.9
	35S	39.37	80.71	30.27		6.1	
				Medelvärden för platta B:		6.1	67.6
	5T1	39.57	79.21	89.98	73.2		
	5T2	39.58	79.62	86.91	70.6		71.9
	5S	39.53	81.13	28.84		5.7	
	15T1	39.65	80.64	85.88	69.6		
C	15T2	39.58	80.91	90.09	73.2		71.4
	15S	39.63	80.78	36.02		7.2	
	35T1	39.62	81.10	83.18	67.5		
	35T2	39.57	80.18	84.37	68.6		68.0
	35S	39.57	80.78	28.27		5.6	
				Medelvärden för platta C:		6.2	70.4
			Medelvärden för hela receptet:			6.3	72.3

Appendix II:7 - Composition no. 7 (former composition no. 4 in [11])

Tryck- och spräckhållfasthet
Betongtyp 4

		d (mm)	ℓ (mm)	Brottkraft (kN)	f_3 (MPa)	f_{SPL} (MPa)	$f_{3,\ medel}$
	5T1	39.52	80.50	104.93	85.5		
	5T2	39.45	80.61	105.13	86.0		85.8
	5S	39.50	80.83	34.46		6.9	
	15T1	39.50	80.56	85.27	69.6		
A	15T2	39.47	80.45	99.05	81.0		75.3
	15S	39.50	81.28	34.56		6.9	
	35T1	39.54	80.04	103.77	84.5		
	35T2	39.47	80.20	103.30	84.4		84.5
	35S	39.46	81.16	30.65		6.1	
				Medelvärden för platta A:		6.6	81.8
	5T1	39.53	80.51	85.59	69.7		
	5T2	39.57	80.33	80.52	65.5		67.6
	5S	39.63	80.48	31.33		6.3	
	15T1	39.57	78.72	88.58	72.0		
B	15T2	39.55	80.36	103.48	84.2		78.1
	15S	39.62	80.60	36.88		7.4	
	35T1	39.65	80.35	106.20	86.0		
	35T2	39.57	80.25	100.17	81.5		83.7
	35S	39.73	80.49	32.72		6.5	
				Medelvärden för platta B:		6.7	76.5
	5T1	39.48	80.00	80.69	65.9		
	5T2	39.50	79.70	81.66	66.6		66.3
	5S	39.50	80.70	34.16		6.8	
	15T1	39.40	80.16	91.79	75.3		
C	15T2	39.45	79.76	87.70	71.7		73.5
	15S	39.43	80.45	42.22		8.5	
	35T1	39.47	80.09	107.82	88.1		
	35T2	39.53	80.00	103.56	84.4		86.3
	35S	39.53	80.94	38.01		7.6	
				Medelvärden för platta C:		7.6	75.3
			Medelvärden för hela receptet:			7.0	77.9

Appendix II:8 - Composition no. 8 (former composition no. 2 in [11])

Tryck- och spräckhållfasthet
Betongtyp 2

		d (mm)	ℓ (mm)	Brottkraft (kN)	f_3 (MPa)	f_{SPL} (MPa)	$f_{3,\ medel}$
	5T1	39.47	79.80	67.71	55.3		
	5T2	39.49	80.06	70.42	57.5		56.4
	5S	39.52	80.69	24.48		4.9	
	15T1	39.53	80.22	61.22	49.9		
A	15T2	39.65	80.11	59.54	48.2		49.1
	15S	39.50	79.97	23.42		4.7	
	35T1	39.44	79.26	70.57	57.8		
	35T2	39.52	80.03	66.09	53.9		55.8
	35S	39.42	80.21	24.48		4.9	
				Medelvärden för platta A:		4.8	53.8
	5T1	39.57	78.12	41.21	33.5		
	5T2	39.53	79.21	45.08	36.7		35.1
	5S	39.68	81.15	21.44		4.2	
	15T1	39.65	79.83	52.57	42.6		
B	15T2	39.68	78.17	52.75	42.7		42.6
	15S	39.54	81.06	17.42		3.5	
	35T1	39.58	80.19	49.65	40.4		
	35T2	39.66	79.41	46.01	37.2		38.8
	35S	39.55	81.12	19.94		4.0	
				Medelvärden för platta B:		3.9	38.8
	5T1	39.50	79.27	55.51	45.3		
	5T2	39.54	79.06	49.87	40.6		43.0
	5S	39.46	81.19	23.25		4.6	
	15T1	39.51	79.85	64.15	52.3		
C	15T2	39.52	77.62	58.96	48.1		50.2
	15S	39.49	81.04	22.58		4.5	
	35T1	39.51	79.48	69.09	56.4		
	35T2	39.46	79.44	65.88	53.9		55.1
	35S	39.54	80.71	28.26		5.6	
				Medelvärden för platta C:		4.9	49.4
			Medelvärden för hela receptet:			4.5	47.3