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EXPERIMENTAL STUDIES ON SHRINKAGE OF HIGH-PERFORMANCE CONCRETE

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ABSTRACT

This article outlines experimental and numerical studies on shrinkage of high-performance concrete (HPC). Carbonation shrinkage especially may introduce surface cracking in concrete, which affects the durability. In order to study shrinkage, cylinders of eight qualities of HPC were investigated. Parallel studies on autogenous shrinkage, drying shrinkage, hydration, internal relative humidity, and strength were carried out. Previous research in the field is summed up. Mechanisms of carbonation shrinkage by modeling correlations to the composition of the HPC and the physical properties are presented. The results indicate that carbonation shrinkage may be avoided by addition of silica fume. The project was carried out from 1992 through 1996. © *1998 Elsevier Science Ltd*

Introduction and Objective

Bazant (1) based the creep and shrinkage model B_3 on fitting of about 15000 data points and about 100 test series. Bazant (1) stated that the model B_3 is not a good description of the autogenous shrinkage, which occurs in sealed concrete. However, Bazant (1) concluded that autogenous shrinkage often is much smaller than drying shrinkage, and is unimportant because it mainly occurs before form stripping, and after form striping only in the core of the concrete. Autogenous shrinkage, a well-known phenomenon caused by the self-desiccation in HPC with low water-cement ratio (w/c), has been pointed out by Persson (2). When the internal relative humidity, Ø, decreases substantially, the depression in the pore water also decreases, which causes compression in the aggregate and the cement paste (3), and self-stress in HPC. Bazant (1) pointed out that further shrinkage might be caused by various chemical reactions, for example carbonation. Bazant (1) found that in good concrete, carbonation occurred only in the surface layer and can be ignored. The objective of the work was to study shrinkage of HPC with w/c < 0.40.

Previous Research on Shrinkage of HPC

Roy and Larrard (4) studied shrinkage of HPC and normal strength concrete, NSC, at different w/c, with different amounts of silica fume. Figure 1 shows the shrinkage at 400

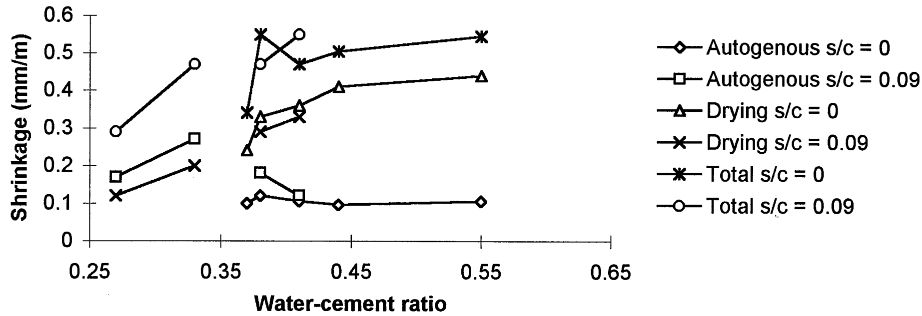

FIG. 1.
Shrinkage at 400 days' age with different amounts of silica fume vs. w/c, Roy and Larrard (4). Symbols: c = cement; s = silica fume.

days' age vs. w/c with different amounts of silica fume. The specimens were 1 m long and 0.16 m in diameter.

The autogenous shrinkage increased at lower w/c. At w/c ≈ 0.3 the autogenous shrinkage after 400 days was about 250 μm/m. The total shrinkage was larger at higher w/c, for example about 600 μm/m at w/c ≈ 0.6. The following conclusions were drawn:

1. The autogenous shrinkage increased with decreasing w/c.
2. The autogenous shrinkage increased when the concrete contained silica fume.
3. The total shrinkage and the sorption shrinkage increased with increasing w/c.

Sicard (5) carried out experiments on 0.12 m diameter cylinders with a length of 0.24 m. Figure 2 shows the result of autogenous shrinkage at 600 days' age vs. time (5).

In this case the water moisture losses were about 1% by the weight of the concrete per year. The following conclusions were drawn:

1. The autogenous shrinkage increased with decreasing w/c.
2. The autogenous shrinkage was larger with limestone aggregate than with sandstone.
3. The autogenous shrinkage was larger in concrete with silica fume than without silica fume.

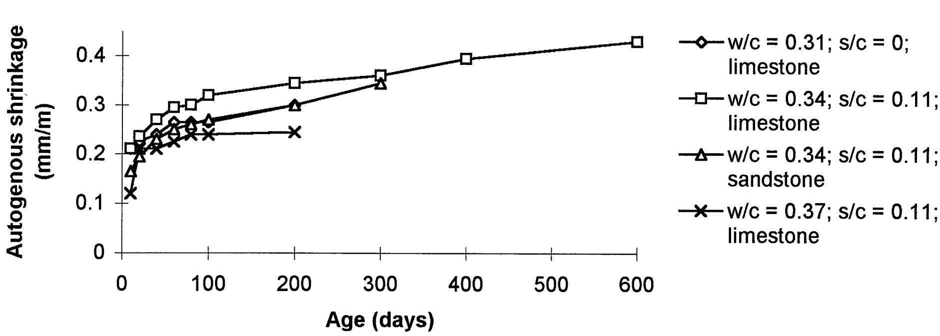

FIG. 2.
Autogenous shrinkage at 600 days' age vs. time, Sicard (5). c = cement; s = silica fume.

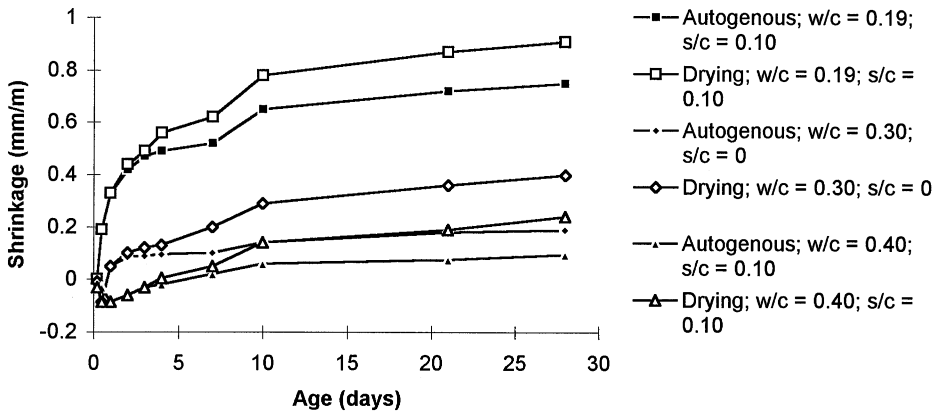

FIG. 3.
Shrinkage at 28 days' age vs. age at different w/c, (6).

Tazawa and Miyazawa (6) studied shrinkage at early ages by cast-in strain gauges. The specimen was 0.1 × 0.1 × 1.2 m. Figure 3 shows the shrinkage at 28 days' age vs. time at different w/c. Concrete was cast in vinyl polymer plastic moulds allowing for early movements of the concrete. The measurements started at ≈ 0.2 days' age. The shrinkage increased with lower w/c and higher content of silica fume. The difference between autogenous and drying shrinkage was small.

Experimental Methods

Table 1 gives the chemical composition of the cement. A total of 52 specimens for studies of autogenous shrinkage and 26 for studies of drying shrinkage were cast from 78 different concrete batches with compositions given in Table 2. After demoulding and insulation by 2 mm butyl rubber clothing (in the case of studies of autogenous shrinkage), 6 stainless steel screws were fixed into cast-in items in the cylinder. Measurements were taken within 1 h from demolding on three sides of the cylinder on a length of 250 mm (7). After cooling, the specimen was placed in a 20 °C climate chamber with a relative humidity (RH) = 55%. Mechanical devices performed the measuring. The measurements of internal RH were carried out on parallel cast specimens that were treated in the same way as the specimen used for measurements of shrinkage. The concrete was crushed and pieces of at least 5 mm in size were placed in glass tubes with a diameter of 25 mm for at least 1 day. After the preparation, a dew point meter was tightly entered into the glass tubes and the RH measured for 1 day. Calibration was carried out according to Standard Practice for Maintaining Constant Relative Humidity, ASTM E 104–85.

TABLE 1
Chemical composition of cement (%).

CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	K_2O	Na_2O	SO_3	CO_2	Free CaO
64.9	22.2	3.36	4.78	0.91	0.56	0.04	2	0.14	1.13

TABLE 2
Mix proportions and main properties of concretes (in kg/m^3 of dry material).

Material	1	2	3	4	5	6	7	8
Quartzite sandstone, 11–16 mm	460	965	910		1010	985		1065
Quartzite sandstone, 8–11 mm	460							
Natural sand, Å 0–8 mm	800	820	790		750	755		690
Granite, N 11–16 mm							1030	
Pea gravel, T 8–16 mm				1095				
Natural sand, B 0–8 mm				780			780	
Cement, low-alkali (302 m^2/kg Blaine)	430	440	445	455	495	530	490	545
Silica fume (fineness 17.5 m^2/g)	21	44	45		50	51		55
Silica fume slurry (fineness 22.5 m^2/g)				23			49	
Air-entraining agent (vinsole resin)	0.02		0.02					
Superplasticizer (melamine formaldehyde)	2.6	4.5	3.8	5.1	4.6	7.6	8.6	10.8
Water-cement ratio	0.38	0.37	0.37	0.33	0.31	0.30	0.30	0.25
Air-content (% by total volume)	4.8	1.1	4.0	0.9	1.1	1.2	1.0	1.3
Density (kg/m^3)	2335	2440	2360	2510	2465	2480	2500	2490
Slump (mm)	140	160	170	45	200	130	45	45
28-day strength, drying cube (MPa)	69	85	69	89	99	106	112	114
1-year strength, drying cube (MPa)	70	89	76	97	109	112	121	125
3-year strength, drying cube (MPa)	69	91		97		115	121	127
28-day strength, sealed cube (MPa)	89	105	95	101	121	126	122	129
1-year strength, sealed cube (MPa)	101	117	98	115	129	145	131	154
2-year strength, sealed cube (MPa)	112			115			131	
3-year strength, sealed cube (MPa)		123	102			141		145

Results from Present Study

In Figure 4 a summary of the shrinkage of concrete 6 is given, vs. age. Figure 5 shows the relative loss of weight (the ratio of weight loss, w_e, to the mixing water, w) vs. time. Figure 6 shows the shrinkage versus the relative loss of weight. The following symbols are used in Figures 4, 5 and 6: c denotes the content of cement (kg/m^3); s denotes the content of silica fume (kg/m^3); w denotes the mixing water (kg/m^3); w_e denotes the weight loss (kg/m^3); and w/c denotes the water-cement ratio

Sources of Error and Accuracy

Minor faults existed due to unforeseen weight losses. The specimens were continuously weighed to detect this loss. After about 1 month's age, carbonation affected the weight of the drying specimens at w/c $>$ 0.30, which caused a combination of drying and carbonation shrinkage. At low w/c $=$ 0.25, no increase of the weight was observed within the period of measurement. Possible absorption of water in the butyl rubber insulation would affect the total weight of the specimen. Three rubber insulation tubes were first placed in an ambient

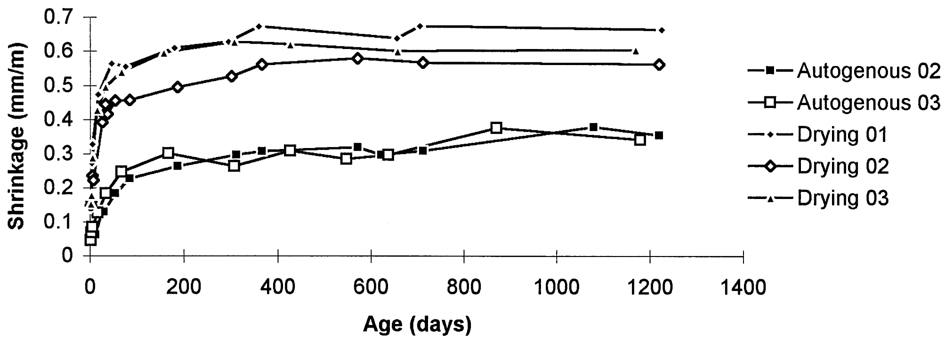

FIG. 4.
Measured shrinkage of concrete 6 at 1200 days' age, Table 2. 02 = concrete batch number.

relative humidity, RH = 40%. After 1 week they were weighed and placed in RH = 55%. No change of weight was observed at RH = 55%. At RH = 95% the weight increased slightly but was hardly detectable, that is, 0.1 g of increased weight. Since the specimen originally contained 120 g of mixing water, the absorption was negligible. Effects of hydration heat in particular were avoided by obtaining the first measurement at 20 °C. A thermocouple was cast in the specimen. The temperature was followed as the first measurement was performed (± 1 °C of difference to 20 °C reducing the observed fault to ≈ 20 μm/m). The variations in the mixed design were normally very small. Only for concrete 6 was a slightly larger difference observed: w/c≈ 0.285 instead of w/c = 0.30. The mechanical devices (Huggenberger and Proceq) were continuously calibrated with an INVAR rod and with a Mitutoyo micrometer. The reading of the device was within 0.005 mm, which was comparable to a maximum fault of 20 μm/m (the length of the device: 250 mm). The total fault of a temperature difference of ± 1°C and the fault of the mechanical device was fairly large, i.e., ≈ 20 + 10 ≈ 30 μm/m. The accuracy of the measurements of the internal relative humidity was estimated to be ± 0.015 after calibration according to the Standard Practice for Maintaining Constant Relative Humidity, ASTM E 104–85.

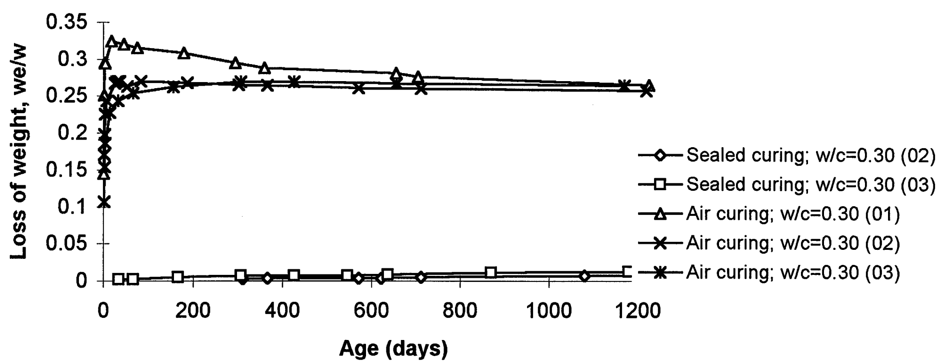

FIG. 5.
Loss of weight of concrete 6 vs. 1200 days' age.

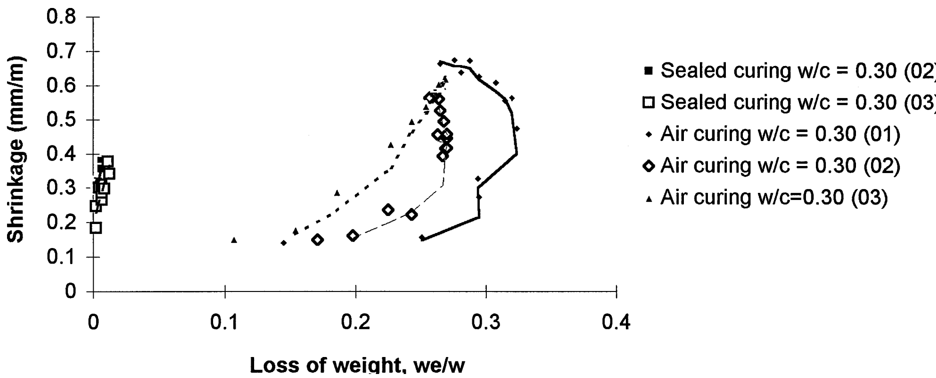

FIG. 6.
Shrinkage vs. loss of weight of concrete 6, Table 2.

Analysis

Autogenous Shrinkage

From a previous work on basic creep of HPC (8), it was observed that the loss of weight for 14 cylinders used in the long-term creep studied was less than 0.7 g per specimen over a period of at least 1 year. (A 0.7 g loss of weight equals $w_e/w = 0.006$.) However, in the present study the joint between the side of the cylinder and the end rubber clothing did not perform perfectly, which may have increased the loss of moisture. Figure 6 shows that small loss of weight may affect the measured shrinkage. Linear regressions were performed to obtain the measured shrinkage at no loss of weight (autogenous shrinkage). In Figure 7, the autogenous shrinkage is given vs. the w/c. The type and the amount of silica fume affected the measured autogenous shrinkage (Fig. 8), which was also observed by others (9). In Figure 9 the autogenous shrinkage is given vs. the internal relative humidity. The type and amount of silica fume affected the autogenous shrinkage (Fig. 10). Silica fume in slurry form had a larger fineness than granulated, with which caused a larger shrinkage. The following correlations were obtained to describe the autogenous shrinkage, ε_B (mm/m):

$$\varepsilon_B = k_s \cdot k_5 \cdot 0.624 \cdot [1 - 2.27 \cdot (w/c)] \; \{R^2 = 0.82\} \tag{1}$$

$$\varepsilon_B = k_{s\text{Ø}} \cdot 1.75 \cdot (1 - 1.13 \cdot \text{Ø}) \; \{R^2 = 0.72\} \tag{2}$$

$$R^2 = 1 - \frac{\sum (Y_i - Y_m)^2}{\left(\sum Y_i^2\right) - \frac{\left(\sum Y_i\right)^2}{n}} \tag{3}$$

where $k_s = 1.5$ for silica fume slurry; $k_s = 1$ for granulated silica fume; $k_{s\text{Ø}} = 1.3$ for silica fume slurry; $k_s = 1$ for granulated silica fume; $k_5 = 0.78$ for 5% silica fume; $k_5 = 1$ for 1% silica fume; n denotes the number of measured values; w/c denotes the w/c {0.2 < w/c <

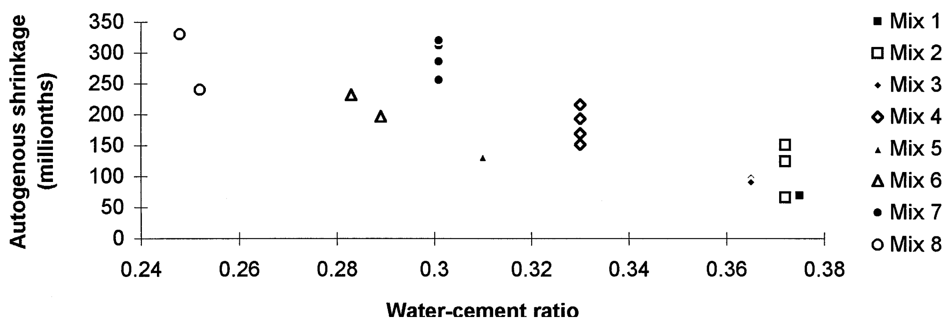

FIG. 7.
Autogenous shrinkage at an age of 3–4 years vs. w/c. The concrete type is given.

0.4}; R^2 denotes an accuracy parameter; Y_i denotes the measured value; Y_m denotes the average measured value; and Ø denotes the internal relative humidity {0.7 < Ø < 0.88}.

Drying Shrinkage of Mature Concrete

Small loss of weight was observed in the sealed specimens for reasons mentioned above. Table 3 shows the loss of weight recorded during a period of at least 3 years from a 1.8 kg concrete specimen. Small loss of weight over a long period simulated well the shrinkage of a large specimen of mature concrete. The relationship between the relative loss of weight, i.e. the ratio of evaporated water to the mixing water made the study non-dimensional. Figure 11 shows the specific shrinkage vs. the ratio of evaporated water to the mixing water, w_e/w:

$$\varepsilon_D = k_{sD} \cdot 20 \cdot [1.1 \cdot (w_e/w) - (w_e/c)] \; \{0 < w_e/w < 0.03; R^2 = 0.71\} \quad (4)$$

where $k_{sD} = 0.4$ for concrete with silica fume slurry; $k_{sD} = 1$ for granulated silica fume; w_e denotes the evaporated water from the concrete (kg/m^3) $\{0 < w_e/w < 0.03\}$; R^2 denotes a correlation parameter given in Eq. 3; and ε_D denotes the specific shrinkage related to the evaporated water (per mil).

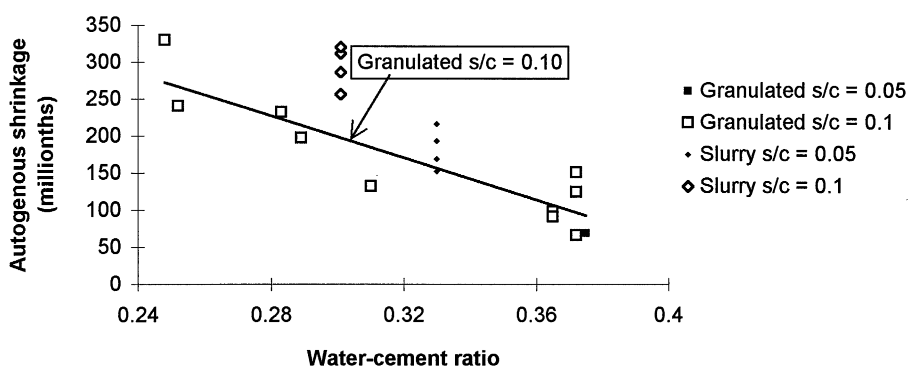

FIG. 8.
Autogenous shrinkage at an age of 3–4 years. The type and amount of silica fume as indicated.

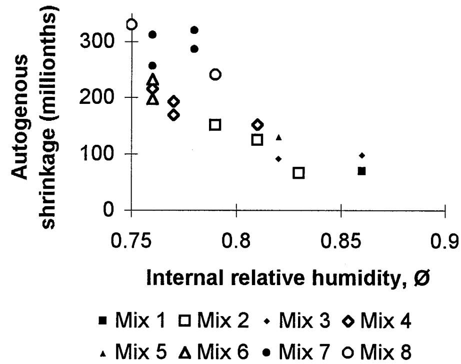

FIG. 9.
Autogenous shrinkage at an age of 3–4 years vs. the internal relative humidity.

Drying Shrinkage of Young Concrete

The internal relative humidity, Ø, of the cylinder in use for the measurements of shrinkage was obtained in the experiments. Between 5 and 28 days' age Ø became less than 0.70, which ceased the effect of hydration and thus the autogenous shrinkage in the specimens (1). However, due to carbonation of the calcium hydroxide of the concrete, the loss of weight ceased at an age of the concrete that was dependent on w/c as shown in Figure 12. [The water in the calcium hydroxide (molecule weight 74) was replaced by the carbon dioxide (molecule weight 100).] When sufficient silica fume was available in the concrete, all the calcium hydroxide was consumed by the pozzolanic reaction according to Eq. 5. In NSC about 16% silica fume is required to consume all the calcium hydroxide (10):

$$3Ca(OH)_2 + 2SiO_2 = 3CaO \cdot 2SiO_2 \cdot 3H_2O \tag{5}$$

At lower w/c the required amount of silica fume, s_{rq}, to consume all the water in the calcium hydroxide became smaller (10,11):

$$s_{rq} \approx [(w/c)/0.39] \cdot 0.16 \approx 0.4 \cdot (w/c) \tag{6}$$

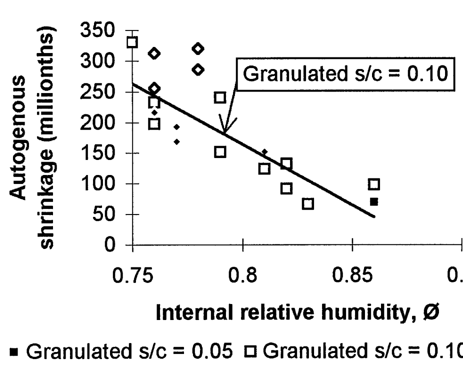

FIG. 10.
Autogenous shrinkage at an age of 3–4 years vs. the internal relative humidity.

TABLE 3
Loss of weight from 1.8 kg specimen (g).

Concrete type	01	02	03	28
1	-	3.9	-	-
2	2.6	2.0	1.1	-
3	2.7	2.3	-	-
4	5.3	2.4	4.2	3.0
5	1.7	1.6	-	-
6	0.7	1.3		
7	3.9	2.5	2.9	5.2
8	0.9	1.0		

According to Eq. 5 carbonation does not occur at w/c = 0.25 and s/c = 0.10. This was confirmed by the experiments as shown in Figure 12. At w/c = 0.3, some of the concretes did not carbonate, which indicated the required amount of silica fume to be slightly lower than estimated in Eq 6. Equation 7 was evaluated for the age at carbonation of HPC with 10% silica fume, t_{ca} (days):

$$t_{ca} = 0.142\cdot(w/c)^{-6.42} \{0.3 < w/c < 0.4; R^2 = 0.67 \qquad (7)$$

For concretes with w/c < 0.3, when carbonation did not occur, the drying shrinkage, ε_{D1}, was correlated to the loss of weight by Eq. 8 (μm/m):

$$\varepsilon_{D1} = 1600\cdot[(w/c) - 0.22]\cdot e^{63\cdot[0.42\cdot(we/w)-(we/c)]} \{0 < w_e/w < 0.30; R^2 = 0.76\} \qquad (8)$$

where c denotes the cement content of the concrete (kg/m^3); e denotes the exponent of the natural logarithm; w denotes the mixing water of the concrete (kg/m^3) {0.25< w/c<0.30}; w_e denotes the evaporated water from the concrete (kg/m^3) {0< w_e/w<0.30}; R^2 denotes a correlation parameter given in Eq. 3; and ε_{D1} denotes the specific shrinkage related to the evaporated water (μm/m).

However, for w/c > 0.3 the carbonation took place simultaneously with the drying of moisture. In this case the shrinkage was correlated to time, which made Eq. 8 dependent on the size of the specimen. (Eq. 7 was non-dimensional.) The time of drying shrinkage was set

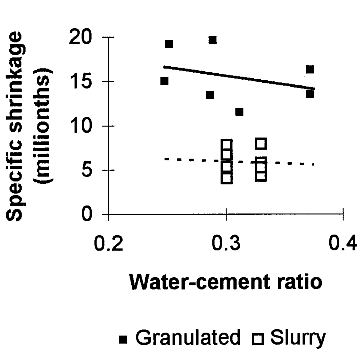

FIG. 11.
Specific shrinkage versus w/c.

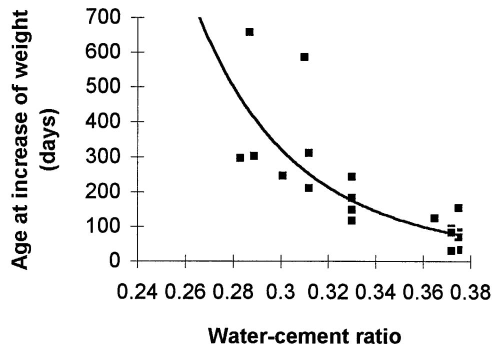

FIG. 12.
Age at increase of weight due to carbonation vs. w/c.

according to Eq. 6. Figure 13 shows the rate of shrinkage. The following equation was obtained [(mm/m)/day]:

$$d\varepsilon_{D2}/dt = k_s \cdot [5.65 \cdot (w/c)^2 - 3.28 \cdot (w/c) + 0.556]/t\{R^2 = 0.86\} \quad (9)$$

where k_s =0.85 for concretes with silica fume slurry; $k_s = 1$ otherwise; and $d\varepsilon_{D2}/dt$ denotes the rate of shrinkage [(mm/m)/day] (diameter: 55 mm; length: 300 mm).

Carbonation of Mature Concrete

At an age as described in Eq. 7 the specimens began to carbonate, which was recorded by weighing. Once the carbonation started, no decline of the internal relative humidity, Ø, occurred. Figure 6 shows the carbonation shrinkage versus the loss of weight. Figure 14 shows the carbonation rate vs. w/c. Table 4 shows the depth of carbonation measured by phenolphthalein.

The carbonation rate, $d(w_c/w)/dt$, was related to age, t, and the mixing water, w [(kg/kg)/day]:

$$d(w_c/w)/dt = 0.25 \cdot [(w/c) - 0.25]/t \ \{0.25 < w/c < 0.40;\ R^2 = 0.73\} \quad (10)$$

where w_c denotes carbonated weight (kg/m^3) $\{0.2 < w_c/w < 0.35\}$.

Equation 10 confirmed Eqs. 6 and 7 that no carbonation occurred with 10% silica fume and w/c < 0.25.

Total Shrinkage

From Figure 15, which shows the different types of shrinkage vs. w/c at varying type and amount of silica fume, the shrinkage after 3 years (4 years for concretes 4 and 7) was correlated:

$$\varepsilon = k \cdot 34 \cdot [(w/c)^2 - 0.68 \cdot (w/c) + 0.13]\ \{R^2 = 0.83\} \quad (11)$$

$$\varepsilon_B = k_B \cdot 1.5 \cdot [0.43 - (w/c)]\ \{R^2 = 0.75\} \quad (12)$$

$$\varepsilon_C = 0.85 \cdot [(w/c) - 0.25]\ \{R^2 = 0.58\} \quad (13)$$

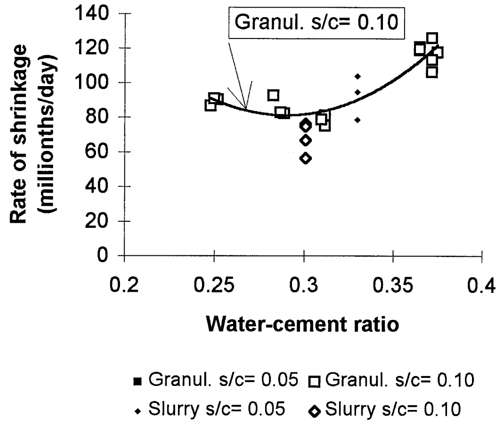

FIG. 13.
Rate of drying shrinkage vs. the w/c. Type of silica fume is indicated.

$$\varepsilon_D = 33\cdot[(w/c)^2 - 0.654\cdot(w/c) + 0.115]\ \{R^2 = 0.53\} \quad (14)$$

where $k = 1.1$ for 10% silica fume slurry; $k = 1$ for 10% granulated silica fume or 5% slurry; $k_B = 1.5$ for 10% silica fume slurry; $k_B = 1$ for 10% granulated silica fume or 5% slurry; ε denotes total shrinkage (mm/m); ε_B denotes basic (autogenous) shrinkage (mm/m); ε_C denotes carbonation shrinkage (mm/m); and ε_D denotes drying shrinkage (mm/m);

Comparison with Other Results

Table 5 shows a comparison with results according to other studies of the estimated shrinkage.

Summary and Conclusions

Initially an introduction of the different kinds of shrinkage of NSC was given together with a summary of previous research on shrinkage of HPC. The experimental methods of measuring

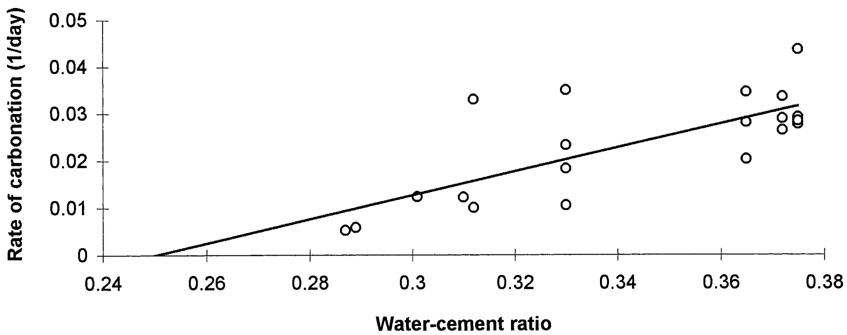

FIG. 14.
Rate of carbonation vs. w/c.

TABLE 4
Depth of carbonation measured by phenolphthalein (one specimen of each concrete only, Table 2).

Concrete	1	2	3	4	5	6	7	8
Depth of carbonation (mm)	7	9	5.5	1	2	1.5	0	0

shrinkage and internal relative humidity were described, with an estimation of the sources of error and the accuracy. Many aspects presented in this paper concerning autogenous and drying shrinkage are not new, and only confirm that some well-known results for NSC also apply for HPC. Few results exist in the literature connecting autogenous shrinkage and self-desiccation. The results presented in this paper concerning carbonation shrinkage are new and original, and likely of general interest. The conclusions indicate the tendencies of results from the experimental studies and also give some brief explanations of the observations (12).

The conditions for carbonation shrinkage of HPC were settled related to w/c and content of silica fume. (At low w/c and high content of silica fume all the calcium hydroxide was consumed in HPC, which more or less eliminated the carbonation and thus also the carbonation shrinkage.) The carbonation rate of HPC was related to age and w/c. The age at the start of carbonation

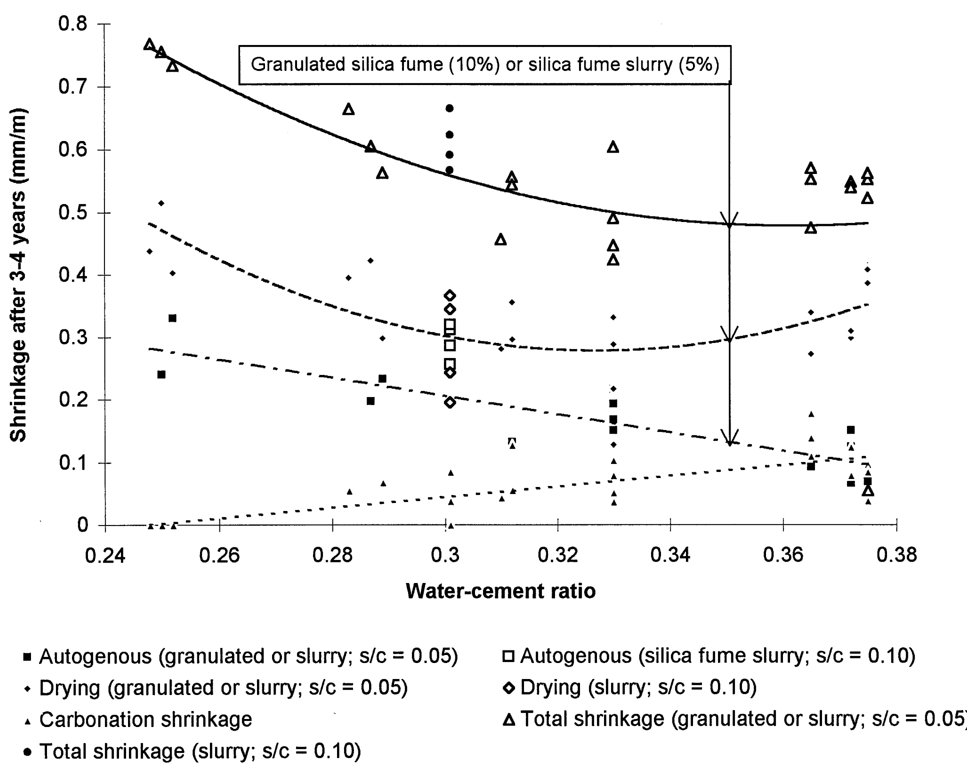

FIG. 15.
Different types of shrinkage after 3 years (4 years for concretes 4 and 7) vs. w/c. Regression lines and type and amount of silica fume are indicated.

TABLE 5
A comparison of results of the estimated shrinkage (μm/m) for w/c = 0.3 and s/c = 0.1.

Study	Bazant (1)	le Roy and Larrard (4)	Sicard (5)	Tazawa and Miyazawa (6)	Persson (8)	Persson (8)	Present study	Present study
Silica fume	-	Granulated	Gran.	Granulated	Gran.	Slurry	Gran.	Slurry
Age (days)	1000	400	600	40	1000	1000	1200	1500
Autogenous	-	220	430	200	320	380	195	295
Drying	15.2	160	-	200	-	-	300	285
Carbonation	-	-	-	-	-	-	45	30
Total	15.2	380	-	400	-	-	540	610

shrinkage of HPC was related to w/c. (At w/c $<$ 0.28 and 10% silica fume, no carbonation shrinkage was observed within 4 years.) The depth of carbonation was related to the carbonation shrinkage. The autogenous shrinkage was dependent on the age, w/c and type and content of silica fume, which also was confirmed by others. The autogenous shrinkage of HPC was related to the decline of internal relative humidity. The decline of pore water pressure during self-desiccation probably is the driving force for the autogenous shrinkage to occur. Therefore, the correlation given in the paper is of general interest. Estimations of drying shrinkage of mature HPC were made related to the evaporated water, which confirms well-known results for NSC. The drying shrinkage was larger than carbonation shrinkage and than autogenous shrinkage together. However, carbonation shrinkage may be more pronounced in the surface of the concrete, causing cracking that influences the durability of the concrete. Like NSC, drying shrinkage of young HPC was related to age and loss of weight. The total shrinkage was related to age, w/c and type and content of silica fume.

Acknowledgment

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