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Eight-year exploration of shrinkage in high-performance concrete

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Abstract

In this paper, an experimental and analytical exploration on the effect of water–binder ratio (w/b), silica fume and age on autogenous, carbonation, drying and total shrinkage of high-performance concrete (HPC) is outlined. Eight types of HPC were studied. Carbonation, internal relative humidity (RH) and strength were studied on specimens from the same batch of HPC that was used in the studies of shrinkage. The results indicate fairly good correlation between carbonation, shrinkage, w/b and RH. The type and amount of silica fume affected shrinkage. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Carbonation; Concrete; High-performance concrete; Long-term performance; Shrinkage; Silica fume

1. Introduction and objective

The long-term behavior of high-performance systems of concrete with water–binder ratio (w/b) < 0.40, as referring to hydration, self-desiccation and strength, has previously been dealt with [1,2]. Strength seems to be increasing continuously provided that the concrete is stored in a sealed condition. Self-desiccation is very pronounced in high-performance concrete (HPC) affecting hydration, which more or less ceases especially at low w/b [3]. Autogenous shrinkage in HPC is caused by the self-desiccation at low w/b, which in turn occurs owing to chemical shrinkage during hydration [4]. When the relative humidity (RH) decreases, the underpressure in the pore water increases, causing compression in the aggregate and cement paste [5,6,7]. Chemical shrinkage also occurs in normal-strength concrete. However, since the pores are larger, it hardly affects RH and shrinkage at all [8,9]. Drying shrinkage may not be measured. It was instead calculated as the difference of total and autogenous shrinkage. When the weight started to increase, drying shrinkage was replaced by carbonation shrinkage. The mechanism of carbonation shrinkage is quite different from that of drying shrinkage. The gas carbon dioxide is present in the laboratory of about 0.1% since it is unventilated. In the presence of moisture, carbon dioxide forms carbon acid, which reacts with calcium hydroxide to form calcium carbonate. Since one molecule of carbon dioxide replaces one molecule of water during this reaction, the weight of concrete increases, too, the molecular weight of carbon dioxide being substantially larger for carbon than for hydrogen [3]. Carbonation proceeds from the surface inwards the concrete, but very slowly especially at low w/b. If all the calcium hydroxide in the concrete is consumed during a pozzolanic reaction, no carbonation will take place, not even in the surface of the specimen. The objective of the work was to obtain appropriate relationships to w/b and RH for final shrinkage of HPC.

2. Experimental methods and material

Tables 1 and 2 present the chemical composition and the main characteristics of the cements and aggregates [8,9]. Nineteen specimens (autogenous shrinkage) and 26 samples (total shrinkage) were cast of eight HPCs (Table 3). All samples were 55 mm in diameter and 300 mm in length. After demoulding and sealing by butyl rubber clothing, six steel screws were fixed to cast-in items in the cylinder 25 mm from each end. The drying specimens were placed in an ambient climate of 20 °C and RH = 60% after 1 day of curing in a steel mould. The maximum temperature was 25 °C at demoulding. The very first temperature movements from measurement at 25 °C until 20 °C and obtained in the

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Table 1
Chemical composition and the characteristics of the cements [8]

X-ray fluorescence analysis (%)	
CaO	64.9
SiO_2	22.2
Al_2O_3	3.36
Fe_2O_3	4.78
MgO	0.91
ICP analysis (%)	
K_2O	0.56
Na_2O	0.04
LECO apparatus (%)	
Ignition losses at 950 °C	0.63
SO_3	2.00
Physical properties	
Specific surface according to Blaine (m^2/kg)	302
Density (kg/m^3)	3220
Setting time	
Vicat (minutes)	135
Water (%)	26.0
Standard test (prisms 40×40×160 mm, MPa)	
1 day	11.0
2 days	20.2
7 days	35.8
28 days	52.6

Table 2
Properties of the aggregate (quartzite sandstone) [9]

Compressive strength (MPa)	Split tensile strength (MPa)	Elastic modulus (GPa)	Ignition losses (%)
333	15	60	0.3

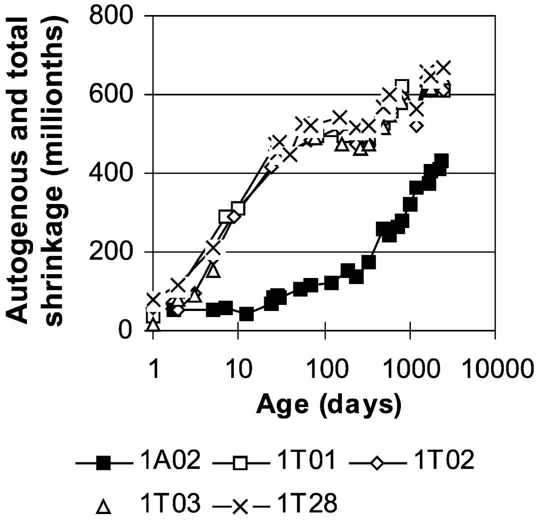

Fig. 1. Measured shrinkage of Concrete 1. A = autogenous shrinkage; T = total shrinkage; 01 = age at start of testing (days).

specimen were compensated for by a thermal coefficient, $\alpha=1.0\times10^{-5}$ [8].

This value of the thermal coefficient was only used during cooling of HPC until about 2 days of age. Measurements were taken by mechanical devices on three sides of the cylinder on a length of 250 mm within 1 h of demoulding [8]. The specimens were placed in a 20 °C climate chamber with RH = 60%. RH was measured by dew point meters on fragment from the strength test. ASTM E 104-85 calibration was performed. From a previous work, it was observed that extremely small loss of weight affected the autogenous shrinkage [10]. The small loss of weight was correlated to the shrinkage (autogenous shrinkage takes place at no weight loss). Carbonation shrinkage started when the weight of the specimen started to increase. The carbonation depth was measured by phenolphthalein on parallel specimens. The weight increase of the specimen solely depended on the carbon dioxide uptake from the air.

Table 3
Mix proportions, etc. (kg/m^3 dry material, etc.) [8]

Material	Mix number 1	2	3	4	5	6	7	8
Quartzite, 8–11 mm	460							
Quartzite, 11–16 mm	460	965	910		1010	985		1065
Sand, Åstorp 0–8 mm	800	820	790		750	755		690
Granite, Norrköping 11–16							1030	
Gravel, Toresta 8–16 mm				1095				
Natural sand, Bålsta 0–8				780			780	
Cement, Degerhamn Std	430	440	445	455	495	530	490	545
Granulated silica fume	21	44	45		50	51		55
Silica fume slurry				23			49	
Air-entraining agent	0.02		0.02					
Superplasticiser	2.6	4.5	3.8	5.1	4.6	7.6	8.6	10.8
Water–binder ratio (1:1)	0.35	0.34	0.33	0.31	0.28	0.26	0.27	0.23
Air content (% by volume)	4.8	1.1	4.0	0.9	1.1	1.2	1.0	1.3
Aggregate content	0.74	0.73	0.72	0.75	0.71	0.70	0.72	0.70
Density (kg/m^3)	2335	2440	2360	2510	2465	2480	2500	2490
Slump (mm)	140	160	170	45	200	130	45	45
28-day drying strength (MPa)	69	85	69	89	99	106	112	114
28-day sealed strength (MPa)	89	105	95	101	121	126	122	129

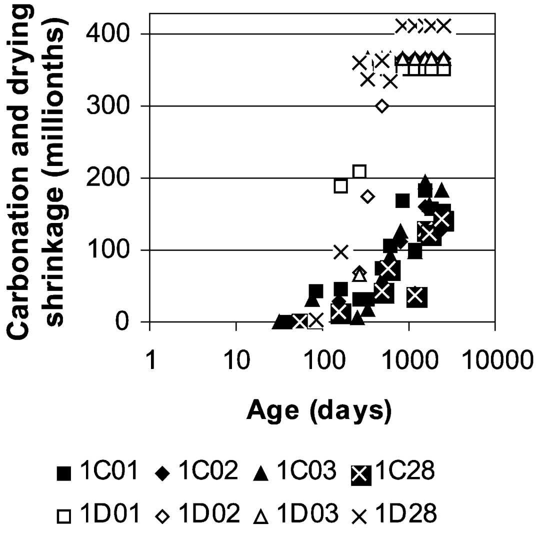

Fig. 2. Calculated shrinkage of Concrete 1. C = carbonation shrinkage; D = drying shrinkage; 01 = age at start of testing (days).

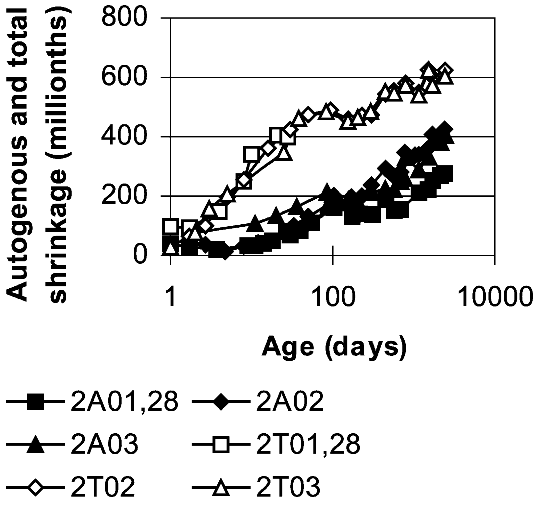

Fig. 3. Measured shrinkage of Concrete 2. A = autogenous shrinkage; T = total shrinkage; 01 = age at start of testing (days).

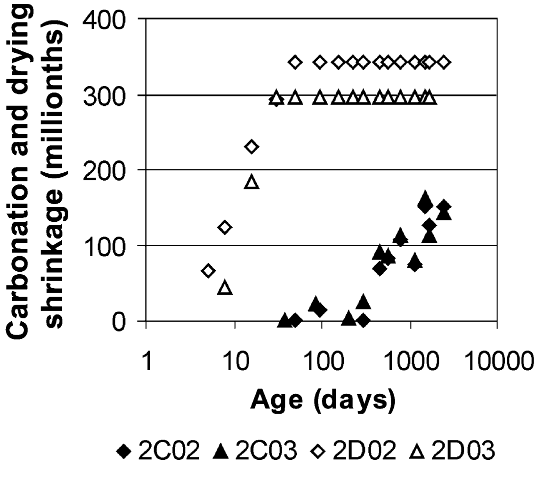

Fig. 4. Calculated shrinkage of Concrete 2. C = carbonation shrinkage; D = drying shrinkage; 01 = age at start of testing (days).

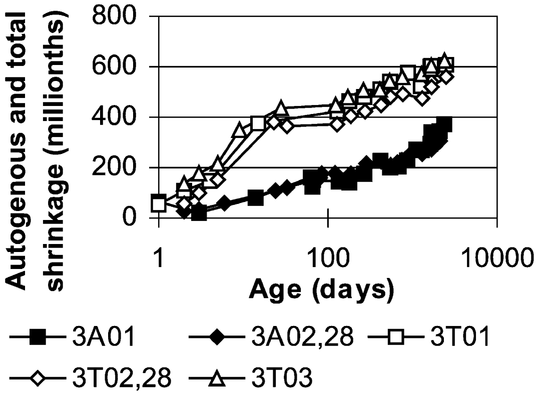

Fig. 5. Measured shrinkage of Concrete 3. A = autogenous shrinkage; T = total shrinkage; 01 = age at start of testing (days).

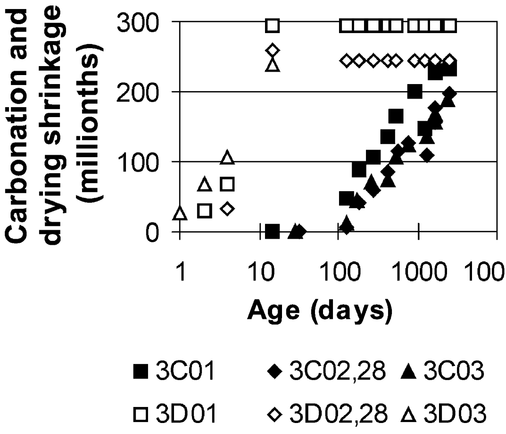

Fig. 6. Calculated shrinkage of Concrete 3. C = carbonation shrinkage; D = drying shrinkage; 01 = age at start of testing (days).

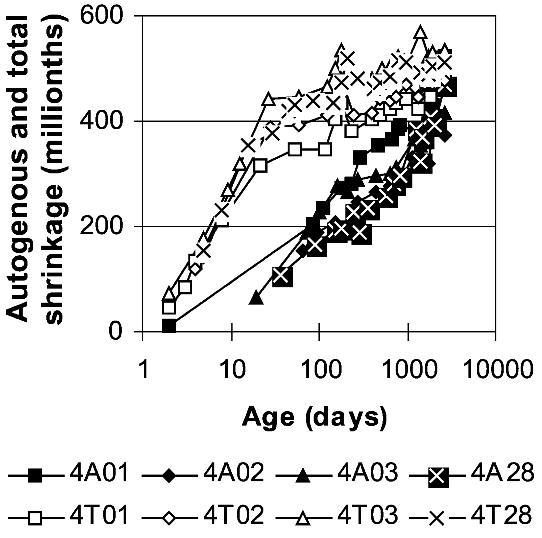

Fig. 7. Measured shrinkage of Concrete 4. A = autogenous shrinkage; T = total shrinkage; 01 = age at start of testing (days).

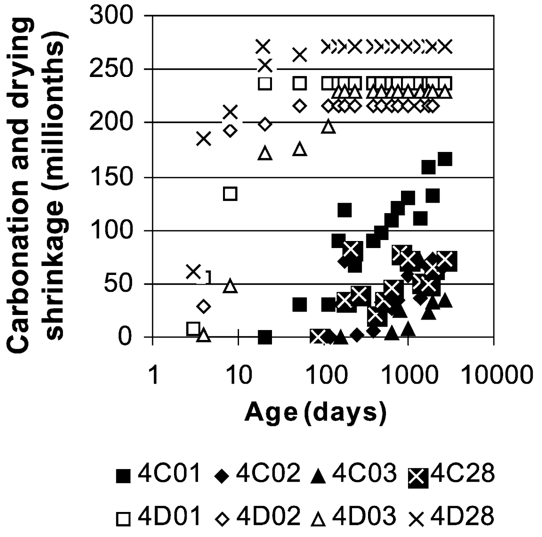

Fig. 8. Calculated shrinkage of Concrete 4. C = carbonation shrinkage; D = drying shrinkage; 01 = age at start of testing (days).

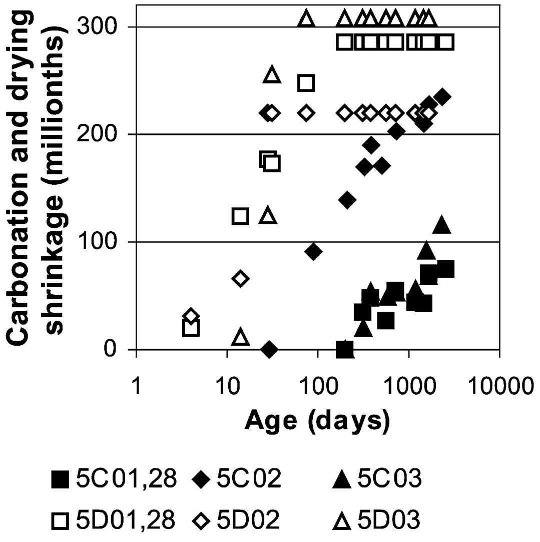

Fig. 10. Calculated shrinkage of Concrete 5. C = carbonation shrinkage; D = drying shrinkage; 01 = age at start of testing (days).

Carbonation is assumed to have no influence on shrinkage in the first 3 months.

3. Results and analysis

Figs. 1–16 show the measured autogenous (A) and total shrinkage (T), the calculated carbonation (C) and drying shrinkage (D, difference among total, autogenous and carbonation shrinkage) versus age that the type of silica fume affected the autogenous shrinkage was also noticed by others [11] (Fig. 17). Fig. 18 shows the autogenous shrinkage versus RH [8,12]. Before estimating the final shrinkage, the water losses mainly after 100 days of age was correlated with the shrinkage. Final autogenous shrinkage was estimated at no weight loss. More or less, linear relationships were found between autogenous shrinkage and w/b [13] and between autogenous shrinkage and RH [14]. Estimation of ultimate autogenous shrinkage, ε_A, was derived with good correlation from Figs. 17 and 18 (silica fume slurry in separate, ‰):

$$\varepsilon_A = 1.55k_s(0.40 - w/b) \qquad \{0.22 < w/b < 0.36\} \tag{1}$$

$$\varepsilon_A = 2(0.89 - RH) \qquad \{0.70 < RH < 0.90\} \tag{2}$$

k_s denotes a factor for HPC with silica fume slurry: $k_s = 1.36$; $k_s = 1.00$, otherwise.

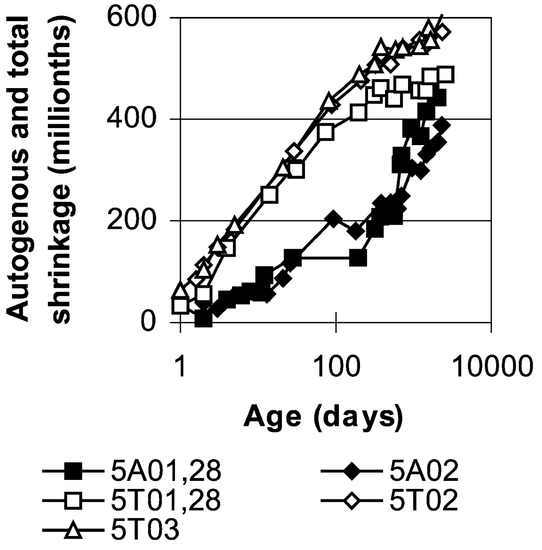

Fig. 9. Measured shrinkage of Concrete 5. A = autogenous shrinkage; T = total shrinkage; 01 = age at start of testing (days).

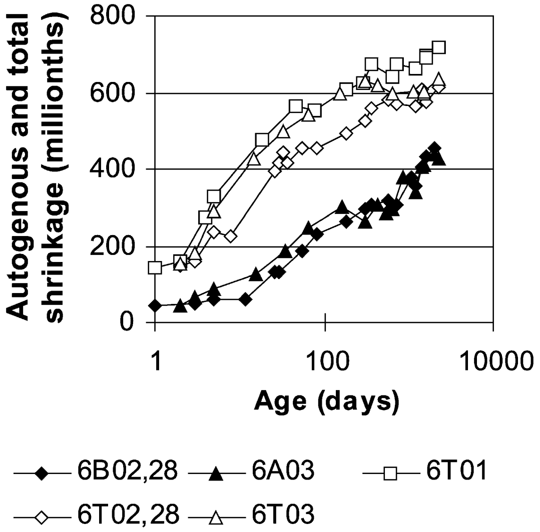

Fig. 11. Measured shrinkage of Concrete 6. A = autogenous shrinkage; T = total shrinkage; 01 = age at start of testing (days).

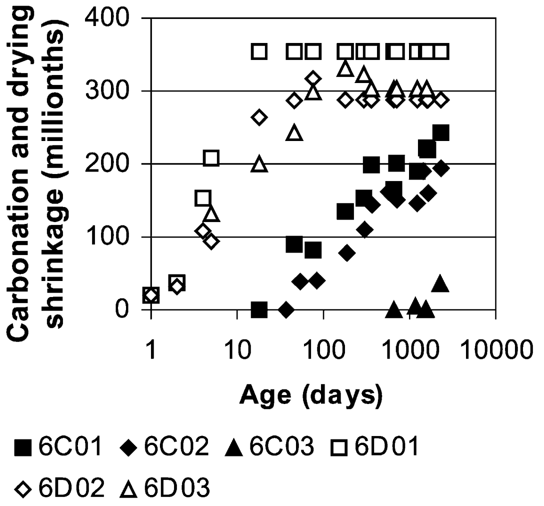

Fig. 12. Calculated shrinkage of Concrete 6. C = carbonation shrinkage; D = drying shrinkage; 01 = age at start of testing (days).

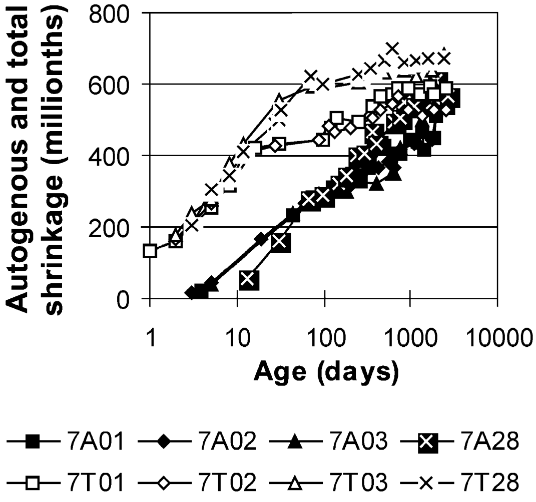

Fig. 13. Measured shrinkage of Concrete 7. A = autogenous shrinkage; T = total shrinkage; 01 = age at start of testing (days).

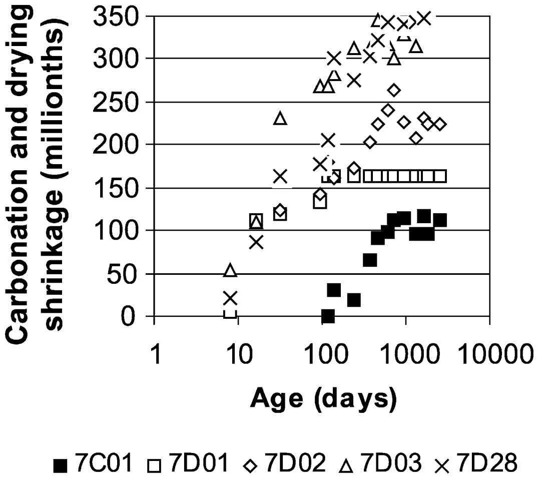

Fig. 14. Calculated shrinkage of Concrete 7. C = carbonation shrinkage; D = drying shrinkage; 01 = age at start of testing (days).

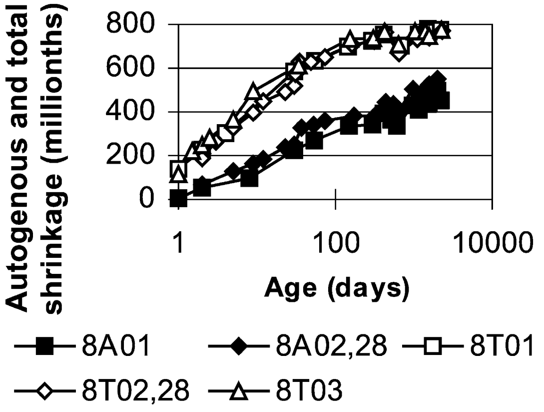

Fig. 15. Measured shrinkage of Concrete 8. A = autogenous shrinkage; T = total shrinkage; 01 = age at start of testing (days).

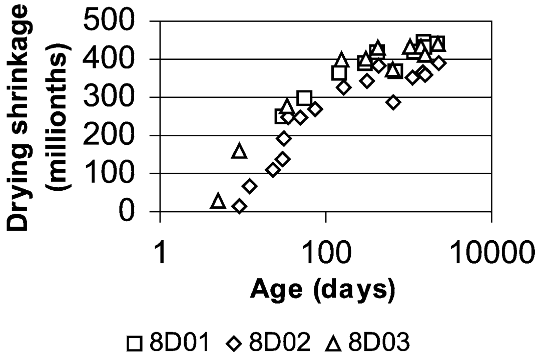

Fig. 16. Calculated shrinkage of Concrete 8. C = carbonation shrinkage; D = drying shrinkage; 01 = age at start of testing (days).

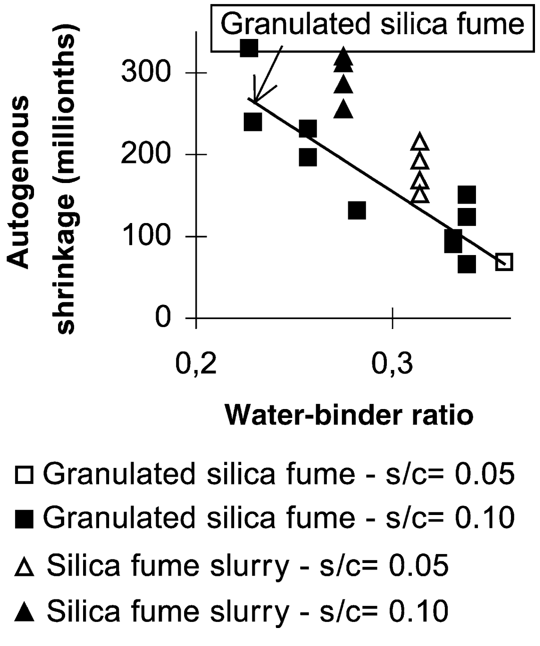

Fig. 17. Autogenous shrinkage versus water–binder ratio. c = cement content; s = amount of silica fume.

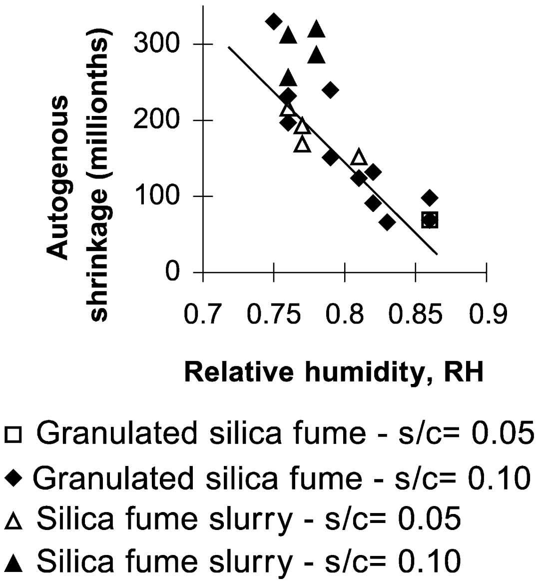

Fig. 18. Autogenous shrinkage versus RH. c = cement content; s = amount of silica fume.

The following calculation was derived on carbonation shrinkage, ε_C (‰) (Figs. 19 and 20):

$$\varepsilon_C = 0.68\text{csp} \; \{\text{csp} = \text{carbonated section part, i.e., carbonated to total area ratio}\}. \quad (3)$$

The drying shrinkage ceased when the minimum weight was obtained in the HPC, i.e., carbonation shrinkage started (Fig. 21). Finally total shrinkage was measured (Fig 22). The following equations were calculated (D=drying, T = total; ‰) (Figs. 21 and 22):

$$\varepsilon_D = 37(w/b)^2 - 22(w/b) + 3.5 \quad \{0.22 < w/b < 0.36\} \quad (4)$$

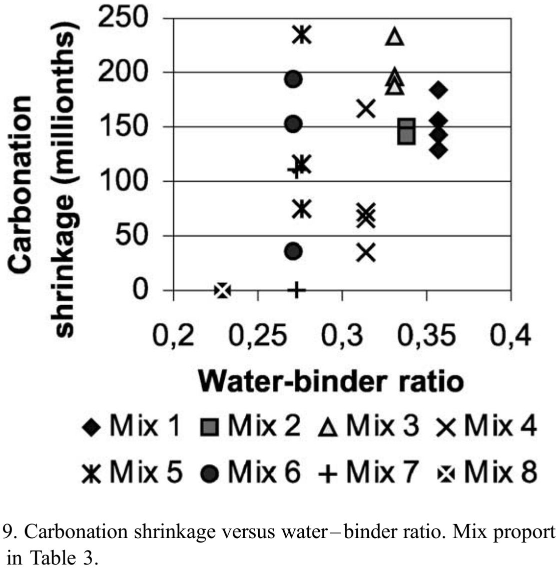

Fig. 19. Carbonation shrinkage versus water–binder ratio. Mix proportions given in Table 3.

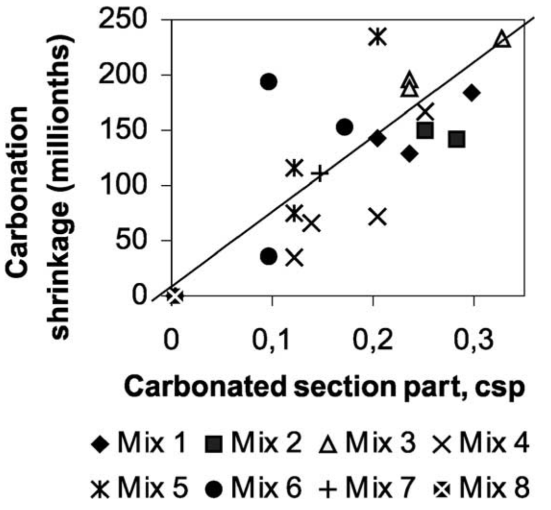

Fig. 20. Carbonation shrinkage versus carbonated to total area ratio, csp. Mix proportions given in Table 3.

$$\varepsilon_T = 38(w/b)^2 - 23.4(w/b) + 4.15 \quad \{0.22 < w/b < 0.36\}. \quad (5)$$

4. Discussion, validation and evaluation according to others

Figs. 23 and 24 show drying and total shrinkage versus the aggregate content [15]. The effect of aggregate on shrinkage was small since most of the HPC mixtures had approximately the same paste content. The effect of RH on shrinkage is well known [14]. Eqs. (1)–(5) are valid for final shrinkage with the following conditions:

1. w/b of HPC varying between 0.22 and 0.36;
2. density of HPC varying between 2350 and 2500 kg/m^3;

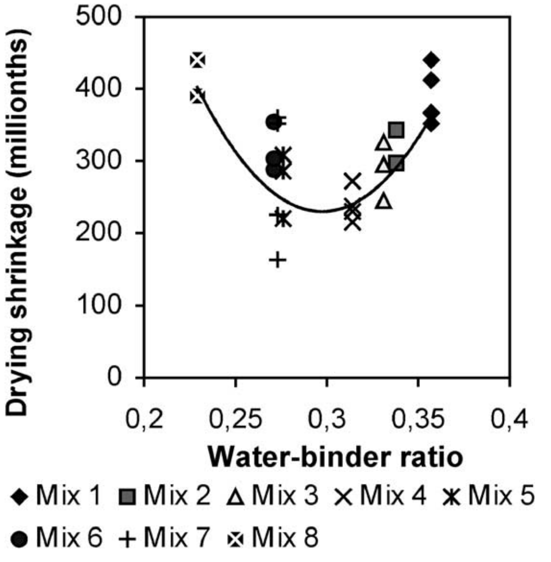

Fig. 21. Drying shrinkage versus water–binder ratio. Mix proportions given in Table 3.

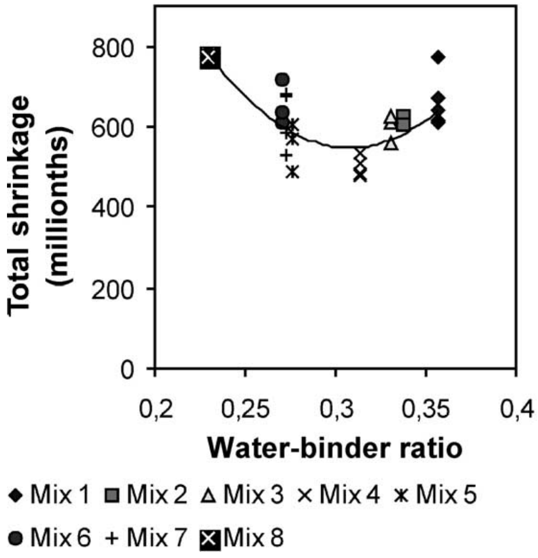

Fig. 22. Total shrinkage versus water–binder ratio. Mix proportions given in Table 3.

3. 28-day strength of HPC varying between 70 and 150 MPa;
4. normal strength and normal elastic modulus of the aggregate;
5. aggregate content between 0.70 and 0.75 (by volume); and
6. ambient climate held at 20 °C and RH = 60%.

Table 4 shows a comparison between this study and results according to others [16,17]. The autogenous shrinkage in this study coincided well with Refs. [15,17,18]. Drying and total shrinkage were larger owing to the age. Carbonation shrinkage was not at all studied by others. By measurement of the carbonated section part and by measurement of carbonation shrinkage, it has been shown that carbonation exists even for HPC. Small loss of weight was observed of the sealed specimens of reasons mentioned above. Table 5 shows the loss of weight recorded during a period of at least 7 years from a 1.8-kg concrete specimen. Small loss of weight over a long period gave a good simulation of the shrinkage of a large specimen of mature concrete.

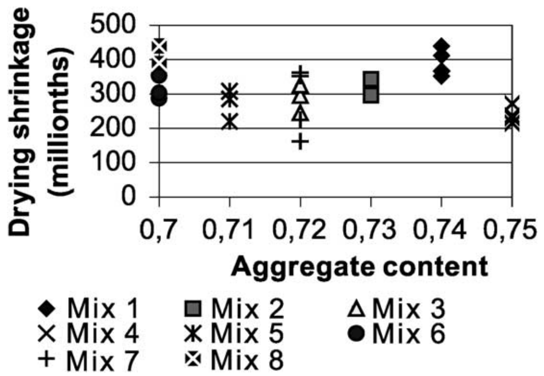

Fig. 23. Drying shrinkage versus aggregate content. Mix proportions given in Table 3.

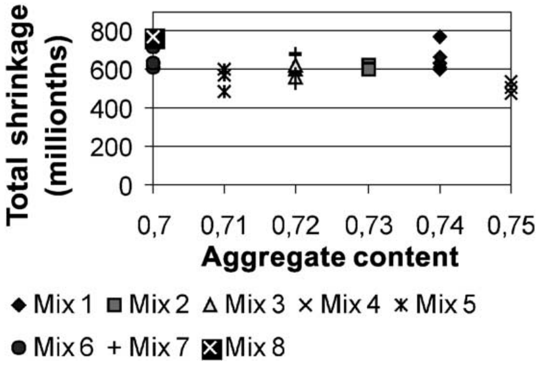

Fig. 24. Total shrinkage versus aggregate content. Mix proportions given in Table 3.

The relationship between the relative loss of weight, i.e., the ratio of evaporated water to the mixing water, made the study nondimensional. The following equation was calculated for drying versus evaporated shrinkage, to the mixing water ratio, w_e/w:

$$\varepsilon_D = k_{sD} 20[1.1(w_e/w) - (w_e/c)] \quad \{0 < w_e/w < 0.03\} \tag{6}$$

c	denotes the cement content of the concrete (kg/m^3)
k_{sD}	0.4 for concrete with silica fume slurry; $k_{sD} = 1$ for granulated silica fume
w	denotes the mixing water of the concrete (kg/m^3)
w_e	denotes the evaporated water from the concrete (kg/m^3) $\{0<w_e/w<0.03\}$
ε_D	denotes the drying shrinkage related to the evaporated water (‰)

RH of the cylinder used for the measurements of shrinkage was obtained in the experiments. Between 5 and 28 days of age, RH became less than 0.70, which ceased the effect of hydration and thus the autogenous shrinkage in the specimens. At 28 days of age, RH of the specimen was still about

Table 4
Results of measured shrinkage for w/b = 0.27 and s/c = 0.1 [millionths (μm/m)]

	Study				
	[15]	[17]	[18]	Present study	Present study
Silica fume	Granulated	Granulated	Granulated	Granulated	Slurry
Age (days)	40	400	600	2400	2400
Autogenous	200	220	430	200	270
Carbonation	Not studied	Not studied	Not studied	140	70
Drying	200	160	Not studied	260	260
Total	400	380	Not studied	600	600

Table 5
Weight loss (g)

Mix	01	02	03	28
1	–	5.0	–	–
2	3.0	2.8	2.2	–
3	4.6	3.5	–	–
4[1]	6.7	3.8	5.6	4.6
5	2.3	2.3	–	–
6	–	1.3	1.9	
7[1]	3.9	2.5	2.9	5.2
8	0.9	1.0		

[1] 8-year loss.

5% larger than the ambient RH. Due to carbonation of calcium hydroxide of the concrete, the loss of weight ceased at an age of the concrete that was dependent on w/b. Water in calcium hydroxide (molecular weight 74) was replaced by carbon dioxide (weight 100). This replacement of water by carbon dioxide was the reason for the increase of weight during carbonation. When sufficient silica fume was available in the concrete, all the calcium hydroxide was consumed by the pozzolanic reaction according to Eq. (7). In normal concrete, about 16% silica fume is required to consume all the calcium hydroxide during the pozzolanic reaction [3,19]:

$$3Ca(OH)_2 + 2SiO_2 = 3CaO \cdot 2SiO_2 \cdot 3H_2O. \qquad (7)$$

At lower w/c, the required amount of silica fume, s_{rq}, to consume all the water in the calcium hydroxide became smaller [3,6,9]:

$$s_{rq} \approx [(w/c)/0.39] \times 0.16 \approx 0.4(w/c). \qquad (8)$$

According to Eq. (8), carbonation does not occur at $w/c = 0.25$ and $s/c = 0.10$, i.e., $w/b = 0.227$. This was confirmed by the experiments as shown in Fig. 19. 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. (8). Eq. (9) was evaluated for the age at start of carbonation of HPC with 10% silica fume, t_{ca} (days) [3]:

$$t_{ca} = 0.142(w/c)^{-6.42} \qquad \{0.3 < w/c < 0.4\}. \qquad (9)$$

For concretes with $w/b < 0.27$, when carbonation did not occur, the drying shrinkage, ε_{D1}, was correlated to the loss of weight by Eq. (10) (μm/m) [3]:

$$\varepsilon_{D1} = 1600[(w/c) - 0.22]e^{63\times[0.42(w_e/w)-(w_e/c)]} \quad \{0 < w_e/w < 0.30\} \qquad (10)$$

c	denotes the cement content of the concrete (kg/m^3)
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) $\{0<w_e/w<0.30\}$
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 with time, which made Eq. (8) dependent on the size of the specimen (Eq. (7) was nondimensional). The time of drying shrinkage was set according to Eq. (6). The following equation was obtained [(mm/m)/day] (Eq. (11)):

$$\delta\varepsilon_{D2}/\delta t = k_s[5.65(w/c)^2 - 3.28(w/c) + 0.556]/t \qquad (11)$$

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

At an age as described in Eq. (9), the specimens began to carbonate, which was recorded by weighing. Once the carbonation started, no decline of the internal RH occurred. No carbonation occurred in concrete with 10% silica fume and $w/c<0.30$, which has been shown on six samples (mixes 7C02, 7C03, 7C28, 8C01, 8C02 and 8C03).

5. Conclusions

The following conclusions were drawn of the 8-year study on shrinkage of HPC:

1. Autogenous shrinkage was defined and calculated at no loss of weight. It was fairly good correlated to w/b and RH and coincided well with results according to others.
2. Carbonation shrinkage started when the weight of the specimen increased, which was observed by length measurement and weighing in parallel. The best correlation was made to the carbonated part of the specimen, i.e., carbonated to total area ratio.
3. Carbonation shrinkage did not occur in HPC with $w/c < 0.30$ and 10% silica fume, which was observed on six specimens.
4. Both drying and total shrinkage had minimums at $w/c = 0.33$ increasing at smaller and larger w/c. Measured long-term shrinkage was larger than others observed.

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