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Autogenous shrinkage of high-strength concrete containing silica fume under drying at early ages

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Abstract

The present study investigated experimentally autogenous shrinkage of high-strength concrete containing silica fume under drying at early ages. The influence of drying on hydration of cementitious materials in the high-strength concrete with water–binder ratios of 0.25, 0.35 and 0.45 was evaluated based on bound water content (BWC), which was exposed to drying at the ages of 0.5, 1.0 and 3.0 days, respectively. By establishing the relationship between the BWC and autogenous shrinkage strain under sealed conditions, autogenous shrinkage strain under drying conditions and drying shrinkage strain were separated from total shrinkage strain, and, then, the contribution of autogenous shrinkage in total shrinkage was discussed. The results showed that the percentage of autogenous shrinkage was macroscopically 50–20% based on the present method, while that was 70–30% based on the conventional superposition principle (SP). The latter resulted in overestimating autogenous shrinkage strain under drying conditions.

Keywords: High-strength concrete; Silica fume; Autogenous shrinkage; Drying shrinkage; Early age

1. Introduction

Unlike in normal-strength concrete, in high-strength concrete, autogenous shrinkage is an important component of volume changes resulting in the occurrence of cracks [1], beside drying shrinkage and temperature deformation. To reduce crack risk of structures made of high-strength concrete, it is necessary to predict accurately strains and stresses produced by volume change, including autogenous shrinkage. Since the timing of strain generation, strain rate and influenced factors of each volume change component may not be necessarily in agreement, it is very important for accurately predicting strain and analyzing the cause of cracks to obtain strain components of volume change. Furthermore, a good grasp of strain component at different ages is very useful to seek the best solution for reducing shrinkage.

A lot of technical literature has investigated the behavior of autogenous shrinkage in high-strength concrete [2,3]. In most, however, attention focused on the behavior of autogenous shrinkage without exchange of moisture between concrete and the exterior environment. Autogenous shrinkage and drying shrinkage were considered as independent phenomena, even when drying has been considered, thereby making the assumption that the principle of superposition is valid between autogenous shrinkage and drying shrinkage. Recently, it was reported that the autogenous shrinkage behavior of concrete under drying conditions differs from that under sealed conditions, making the superposition principle (SP) inapplicable [4–6].

This study focuses on the behavior of autogenous shrinkage and drying shrinkage of high-strength concrete under drying conditions. The influence of drying on the hydration of cement in high-strength concrete containing silica fume was investigated experimentally in terms of bound water content (BWC). By establishing the relationship between BWC and autogenous shrinkage strain, autogenous shrinkage strain under drying conditions and drying shrinkage strain was separated from total shrink-

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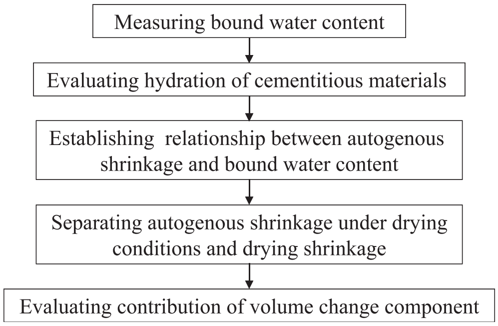

Fig. 1. Procedure of present method for evaluating autogenous shrinkage under drying condition.

age strain, and the contribution of autogenous shrinkage in total shrinkage under different curing conditions and water–binder ratios was evaluated.

2. Method of evaluation of autogenous shrinkage under drying

Because autogenous shrinkage is a phenomenon caused by the negative pressure due to self-desiccation with hydration process [7], it is effected by moisture and pore structure (pore distribution and porosity) [8–10], the driving forces of autogenous shrinkage. In concrete exposed to drying, the hydration of cement is disturbed by the reduction of water supply around cement particles, thereby making the BWC (an index of hydration degree) decrease and pore structure change. Considering the influence of drying on hydration, it is expected that autogenous shrinkage under drying conditions differs from that under sealed conditions, especially in the case of concrete dried at an early age.

As Koenders and Van Breugel [11] have indicated, the development of autogenous shrinkage can be presented as a function of the degree of hydration. Additionally, recent research [12] has described how hardened cement paste that was dried at an early age and then supplied with moisture again is similar in pore distribution to water-cured paste for the same degree of hydration. Therefore, it should be reasonable to assume autogenous shrinkage to be a function of the degree of hydration in cement even under drying conditions. Based on the above reasoning and noting that BWC can be measured directly at any given age, it is assumed in this study that autogenous shrinkage is a function of BWC only, even under drying conditions.

Table 1
Materials

Material	Properties
Cement (C)	Ordinary Portland cement; specific gravity: 3.14; Blaine: 3220 cm^2/g
Silica fume (SF)	Specific gravity: 2.20; Blaine: 2×10^5 cm^2/g; SiO_2: 91%
Fine aggregate (S)	Kinu River sand; F.M.: 2.93; specific gravity: 2.58
Coarse aggregate (G)	Kinu River crushed stone; F.M: 6.75; specific gravity: 2.63
Superplasticizer (SP)	Polycarbonate-type superplasticizer

Table 2
Mix proportions of concrete

No.	W/B	SF/B (%)	s/a (%)	Unit content (kg/m^3)					
				W	C	SF	S	G	SP (× B)
C-SF25	.25	10	41	160	576	64	659	966	1.80%
C-SF35	.35	10	43	167	424	47	747	1009	1.80%
C-SF45	.45	10	45	170	340	38	775	1048	1.40%

B = C + SF; s/a: percentage of fine aggregate by volume.

Fig. 1 shows the procedure of the present method for evaluating autogenous shrinkage under drying conditions. First, the hydration development of cementitious materials in high-strength concrete containing silica fume under drying is evaluated quantitatively, based on BWC. Subsequently, the relationship between autogenous shrinkage strain under sealed conditions and BWC is established. Finally, autogenous shrinkage strain under drying conditions and drying shrinkage strain are separated from total shrinkage strain by using the relationship.

3. Experimental program

3.1. Materials and mix proportions

The materials and mix proportions of the high-strength concrete used in this study are shown in Tables 1 and 2; ordinary Portland cement and silica fume were used as binders.

3.2. Shrinkage

Specimens 100 × 100 mm in cross-section and 400 mm in length were used for autogenous shrinkage and total shrinkage tests.

To free concrete deformation from restraint, foamed polystyrene sheets and teflon sheets as well as polyethylene films were placed between the concrete and the mold as shown in Fig. 2. After casting, the molded specimens were covered with polyethylene films and wet fabrics to prevent water evaporation.

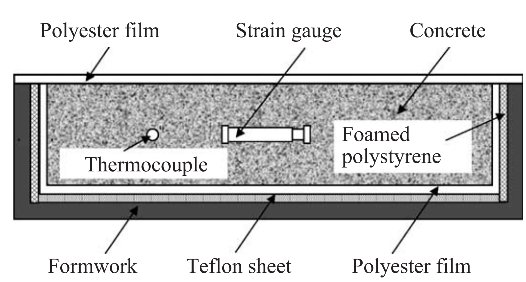

Fig. 2. Outline of specimen for shrinkage test.

Table 3
Age at BWC measurement

Drying initiation age	Measuring age (days)
Sealed	0.5, 0.625, 0.75, 1, 1.5, 3, 5, 7, 10, 14, 28, 60, 90
0.5 days	0.5, 0.625, 0.75, 1, 1.5, 3, 5, 7, 10, 14, 28, 60, 90
1 day	1, 1.5, 3, 5, 7, 10, 14, 28, 60, 90
3 days	3, 5, 7, 10, 14, 28, 60, 90

Specimens for autogenous shrinkage were demolded at the age of 0.5 days and then sealed with aluminum adhesive tape.

For total shrinkage specimens, aluminum adhesive tape was left in place at both ends even after initiation of drying so as to obtain the same ratio of volume to surface area exposed to drying (V/S) as specimens in the BWC test described later. Drying begun at 0.5, 1 and 3 days.

Shrinkage strain was measured by means of a strain gauge embedded in the center of each specimen along with thermocouples. As Pickett [13] has pointed out, a distribution of shrinkage strain occurs across the section after initiation of drying, so the strain obtained with the embedded strain gauge in this study is the average value including the influence of internal restrained stress due to the strain distribution within the section, and the value was used for evaluating the average behavior of shrinkage of a cross-section. The climate conditions for all specimens featured a temperature of 20 ± 1 °C and humidity of $60 \pm 5\%$.

3.3. Bound water content

The sample for measuring BWC was from a compressive test specimen. To obtain the same V/S as for the shrinkage test specimen, both ends of the compressive test specimen (ϕ 100×200 mm) were kept sealed with aluminum adhesive tape even after drying.

After compressive testing at specified ages, both end sections of the specimen were cut off to a length of 50 mm. The remainder of the specimen was crushed into particles of approximately 2.5–5 mm in size and then mixed. The sample used for measurement of BWC was obtained with sample splitter from the particles and the mass of the sample was about 30 g. Immediately after measuring the mass, the sample was repeatedly immersed in acetone to terminate the hydration reaction. After drying the sample in an oven for 12 h at 105 °C, it was heated to 1000 °C in an electric furnace for 4 h. The values of BWC obtained with the above method are the average value of a cross-section, and the influence of gradient of the degree of hydration over the cross-section is neglected based on the purpose of this study that focuses on the average behavior of shrinkage of a cross-section.

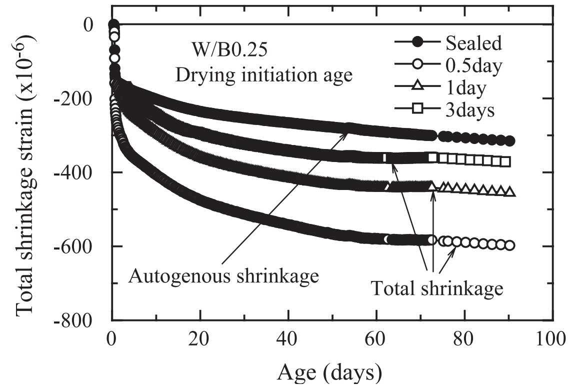

Fig. 4. Time-dependent change in total shrinkage strain (W/B0.25).

BWC was defined as the mass of water combined with the unit mass of the binder. The mass of the binder was determined by a method using hydrochloric acid solution. The BWC value given is the average value of two samples obtained from different compressive test specimens. BWC was measured at the specified ages shown in Table 3.

4. Results and discussions

This clearly shows that the thermal expansion coefficient of high-strength concrete is not constant at early ages. However, in the case of 20 °C curing, the values of maximum temperature rise after initial setting are 2.4 °C

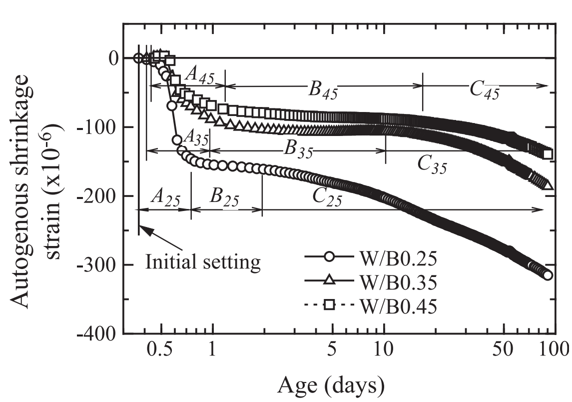

Fig. 3. Time-dependent change in autogenous shrinkage.

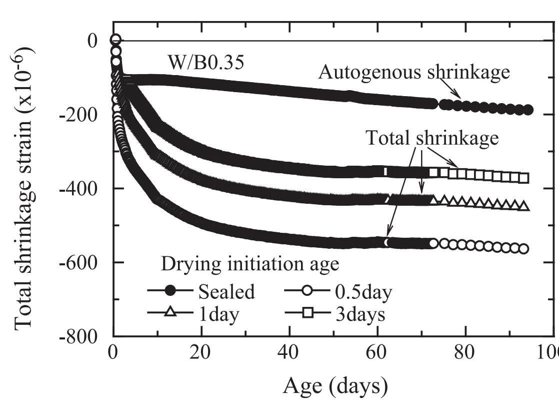

Fig. 5. Time-dependent change in total shrinkage strain (W/B0.35).

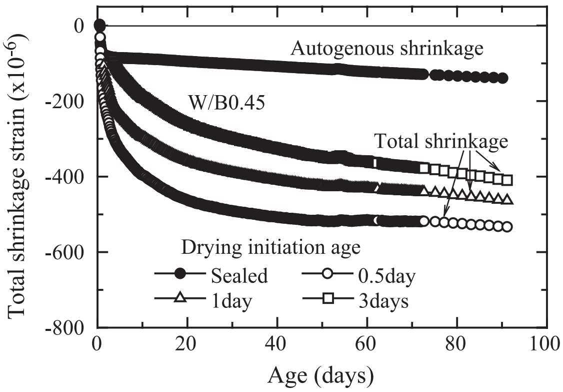

Fig. 6. Time-dependent change in total shrinkage strain (W/B0.45).

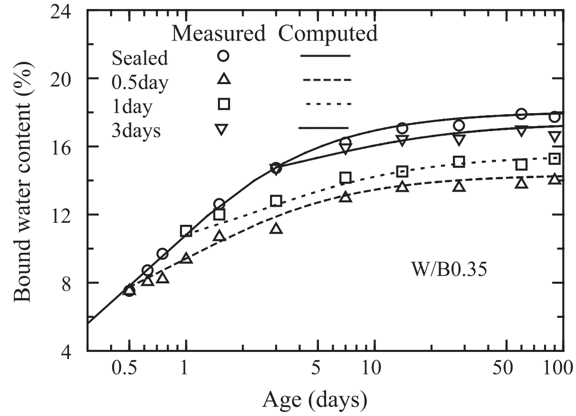

Fig. 8. Influence of drying initiation age on BWC (W/B0.35).

for W/B0.25%, 1.8 °C for W/B0.35% and 1.7 °C for W/B0.45%. These temperature rises caused by heat of hydration are small, and the contribution to strain of the thermal expansion coefficient is negligible. The thermal expansion coefficient was assumed to be a constant value of 10×10^{-6}/K in this study, and shrinkage strain was obtained by subtracting the temperature strain based on the coefficient.

4.1. Autogenous shrinkage under sealed conditions and total shrinkage

Autogenous shrinkage strain was defined as any strain increment after initial setting. In this study, the initial setting times were about 0.37 days for W/B0.25, 0.41 days for W/B0.35, and 0.46 days for W/B0.45.

As shown in Fig. 3, the autogenous shrinkage strains under sealed conditions developed rapidly at early ages, but slowly at later ages. In particular, the development of autogenous shrinkage could be divided into three stages: an early rapidly increasing stage *A*, a stable stage *B*, and a late gradually increasing stage *C*. This characteristic is considered to correspond to a change in the internal structure of concrete. As Takahashi et al. [14] have pointed out, *A* corresponds to a rapid change in the fine pore structure after setting, namely, reduction of porosity and pore size; *B* corresponds to the formation of a strong solid skeleton; and *C* corresponds to the phenomenon in which ettringite decomposes due to the consumption of gypsum. The lower the water–binder ratio is, the shorter the periods of *A* and *B* are, and the earlier *C* starts.

A lower water–binder ratio results in greater autogenous shrinkage strain. The autogenous shrinkage strains in the cases of W/B0.45 and W/B0.35 at the age of 90 days are about 139×10^{-6} and 186×10^{-6}, respectively. The autogenous shrinkage strain in W/B0.25 is more than twice as large as that in W/B0.45, reaching a value of 315×10^{-6}. Furthermore, in the case of W/B0.25, the changes in autogenous shrinkage strain are 155×10^{-6} between initial setting time and 1 day, and 160×10^{-6} between 1 and 90 days. Correspondingly, the changes are 90×10^{-6}, 96×10^{-6} for W/B0.35, and 72×10^{-6}, 67×10^{-6} for W/B0.45. About half of the autogenous shrinkage strain at the age of 90 days was generated before 1 day.

Total shrinkage strains of concrete dried at different ages are shown in Figs. 4–6. For comparison, autogenous shrinkage strains under sealed conditions are also indicated in these figures. For a given W/B, an earlier drying initiation

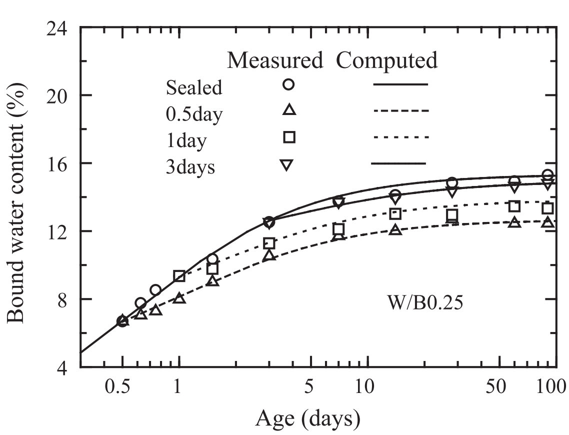

Fig. 7. Influence of drying initiation age on BWC (W/B0.25).

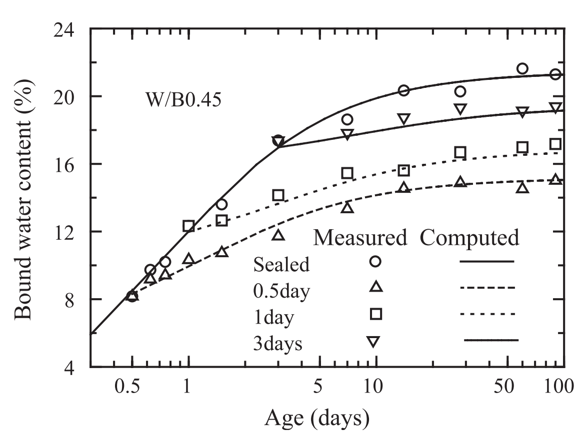

Fig. 9. Influence of drying initiation age on BWC (W/B0.45).

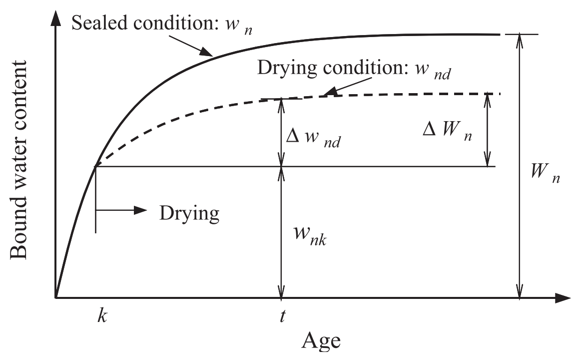

Fig. 10. Schematic illustration of hydration development.

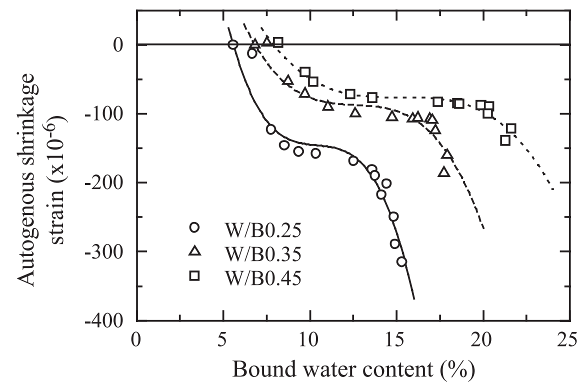

Fig. 11. Relationship of autogenous shrinkage strain and BWC.

age results in larger total shrinkage strain. But for a given age at initiation of drying, the difference of strains between different W/B is not significant. Neglecting the influence of W/B, and evaluating total shrinkage strain at the age of 90 days on average, the values of total shrinkage strain of concrete are 560×10^{-6} when drying begins at age 0.5 days, 450×10^{-6} drying from 1 day, and 380×10^{-6} from 3 days, respectively.

4.2. Influence of drying on hydration development of high-strength concrete

The time-dependent changes of measured BWC of concrete with W/B0.25, W/B0.35, and W/B0.45 are shown in Figs. 7–9, respectively.

The BWC increased rapidly at early ages, but slowly at later ages. After the age of 28 days, it showed a tendency to converge. The lower the water–binder ratio is, the more notable the tendency is.

Although the variation in BWC for different water–binder ratios is small at an early age, as the concrete ages, the lower the water–binder ratio is, the more the BWC drops. For all water–binder ratios, binder hydration was disturbed when under drying conditions, and the BWC seen under drying conditions was smaller than that under sealed conditions. The later the initiation of drying, and the lower the water–binder ratio, the smaller is the difference between sealed and drying BWC. In particular, in the case of W/B0.25, the influence of drying on BWC was very small when drying began at the age of 3 days.

According to Nagamatsu et al.'s [15] research and the author's modification [16], the time dependence of BWC can be described as follows:

Under sealed conditions,

$$w_n = \frac{W_n t}{t + \dfrac{1}{a_s W_n}} \tag{1}$$

where, as shown in Fig. 10, w_n is BWC at age t under sealed conditions, W_n is ultimate BWC under sealed conditions, and a_s is a coefficient describing the hydration rate under sealed conditions.

Under drying conditions,

$$w_{nd} = w_{nk} + \frac{\Delta W_{nd}(t-k)}{(t-k) + \dfrac{1}{a_d \Delta W_{nd}}} \tag{2}$$

where, w_{nd} is BWC at age t under drying conditions, w_{nk} is BWC at drying initiation age k (obtained using Eq. (1)), ΔW_{nd} is the increment in BWC from drying initiation age t to the ultimate age, $\Delta W_{nd} = W_{nd} - w_{nk}$, W_{nd} is ultimate BWC under drying conditions, and a_d is a coefficient describing the hydration rate under drying conditions.

In this study, W_{nd}, a_s, ΔW_{nd}, and a_d were obtained by regression analysis from experimental data up to the age of 90 days, since the scope of the study is limited to high-strength concrete with a low water–binder ratio. These results are summarized in Table 4. Figs. 7–9 show a good agreement between measurement and computation results.

Table 4
Coefficients

No.	Drying initiation age	W/B		
		0.25	0.35	0.45
W_n	Sealed	15.36	18.06	21.45
a_s	Sealed	0.100	0.083	0.059
ΔW_{nd}	0.5	6.02	6.61	6.85
	1	4.56	4.66	4.85
	3	2.34	2.61	2.41
a_d	0.5	0.105	0.102	0.089
	1	0.088	0.064	0.054
	3	0.067	0.053	0.039

Table 5
Constants a, b, c, and w_0

W/B	0.25	0.35	0.45
a	− 86.04	− 42.94	− 31.49
b	17.34	7.23	4.32
c	− 1.20	− 0.41	− 0.20
w_0	5.57	6.82	7.89

4.3. Evaluation of shrinkage strain

4.3.1. Relationship between autogenous shrinkage strain and BWC

As shown in Fig. 11, autogenous shrinkage strain increases with BWC. The relationship between autogenous shrinkage strain $\varepsilon_{as,s}$ under sealed conditions and BWC can be described as a multinomial function shown in Eq. (3).

$$\varepsilon_{as,s} = a(w_n - w_0) + b(w_n - w_0)^2 + c(w_n - w_0)^3 \quad (3)$$

where, w_0 is BWC at the initial setting time, and a, b, and c are constants depending on W/B. The values of the constants obtained with regression analysis are shown in Table 5.

Having assumed autogenous shrinkage strain to be a function of BWC only, autogenous shrinkage under drying condition $\varepsilon_{as,d}$ can be obtained using Eq. (3) by replacing w_n with w_{nd}.

Subtracting the autogenous shrinkage strain under drying condition $\varepsilon_{as,d}$ (obtained above) from total shrinkage strain ε_{total}, $\varepsilon_{as,d}$ drying shrinkage strain can be obtained.

4.3.2. Autogenous shrinkage under drying conditions

Autogenous shrinkage strain under drying conditions and drying shrinkage strain can be obtained by one of two methods. The first is based on an SP which assumes autogenous shrinkage under drying conditions to be equal to that under sealed conditions. The other method is based on an evaluation of hydrate development by means of BWC, considering the reduction in autogenous shrinkage due to drying as shown in Fig. 1. The components of shrinkage are shown in Figs. 12–14. The autogenous shrinkage strain calculated by the SP method for drying conditions is an overestimate, as compared with that obtained by BWC. The difference between SP and BWC results is evaluated here in terms of an overestimation ratio α defined in Eq. (4), in which shrinkage strains at the age of 90 days are used.

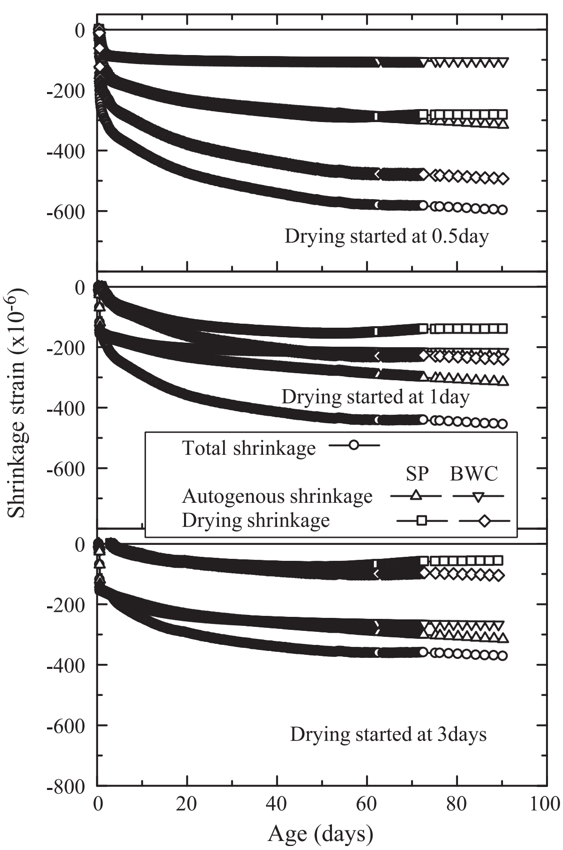

Fig. 12. Components of shrinkage (W/B0.25).

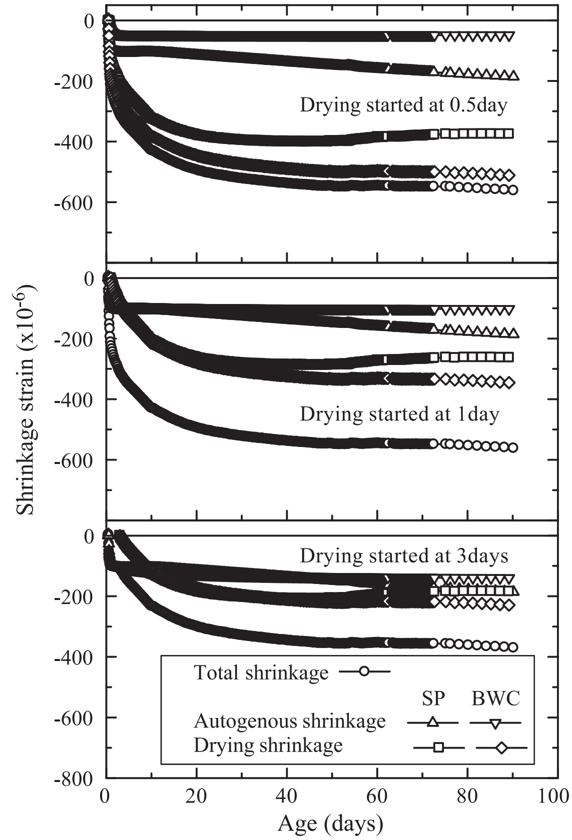

Fig. 13. Components of shrinkage (W/B0.35).

$$\alpha = \frac{\varepsilon_{sp} - \varepsilon_{bwc}}{\varepsilon_{bwc}} \times 100\% \quad (4)$$

where, ε_{sp} is autogenous shrinkage strain under drying conditions obtained with SP, and ε_{bwc} is autogenous shrinkage strain under drying condition obtained with BWC.

The overestimation ratios are shown in Fig. 15. For a given W/B, the earlier the drying initiation age is, the more significant the influence of drying is, and the larger the difference of autogenous shrinkage strain obtained by the two evaluation methods is. Except for when the drying initiation age is 0.5 days, for a given drying initiation age, the larger the W/B is, the more significant

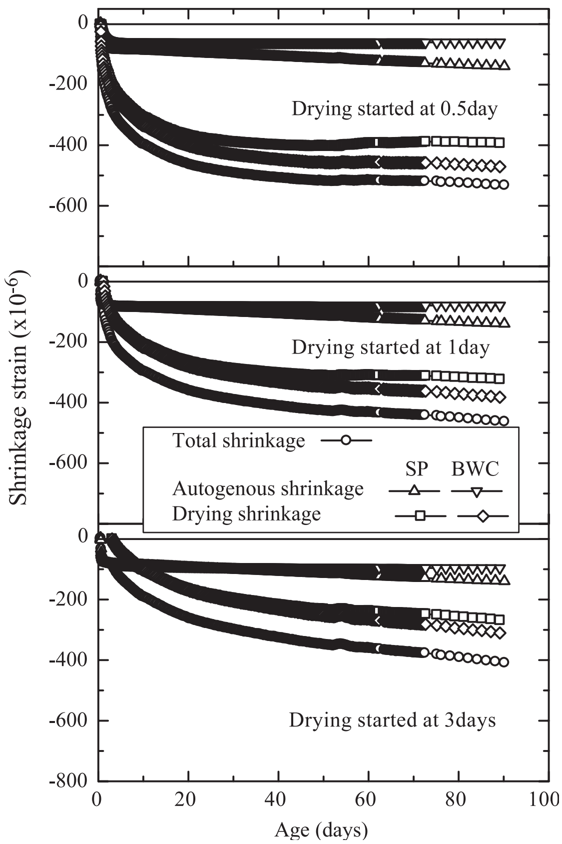

Fig. 14. Components of shrinkage (W/B0.45).

the influence of drying is, but the difference in strain is not so significant.

As shown in Fig. 15, if concrete with W/B0.25 is exposed to drying conditions from an age of 3 days, the overestimation ratio will be less than 20% when autogenous shrinkage strain under drying is taken to be the same as that under sealed conditions.

4.3.3. Contribution of autogenous shrinkage strain

The ratio of autogenous shrinkage strain under drying conditions to total shrinkage strain is defined as the contribution of autogenous shrinkage, based on the results of the separation of strains obtained by BWC. Fig. 16–18 show the time-dependent changes in this contribution.

As shown in the figures, for any drying initiation age, the contribution of autogenous shrinkage strain decreases with time as drying proceeds, and the fall is rapid when

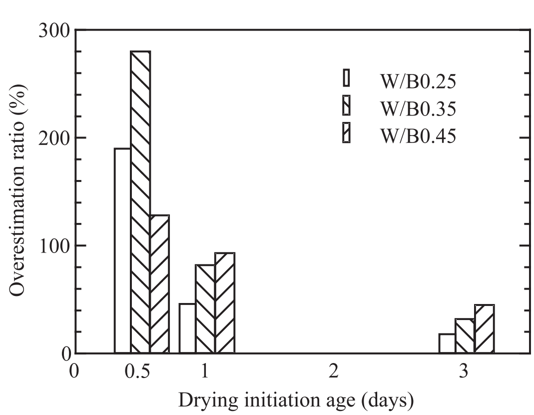

Fig. 15. Overestimation ratio of SP method compared with BWC method.

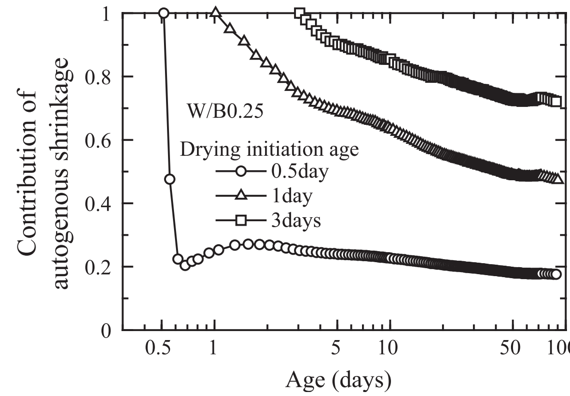

Fig. 16. Contribution of autogenous shrinkage (W/B0.25).

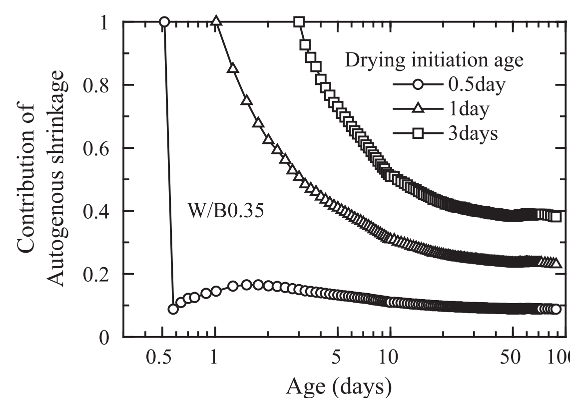

Fig. 17. Contribution of autogenous shrinkage (W/B0.35).

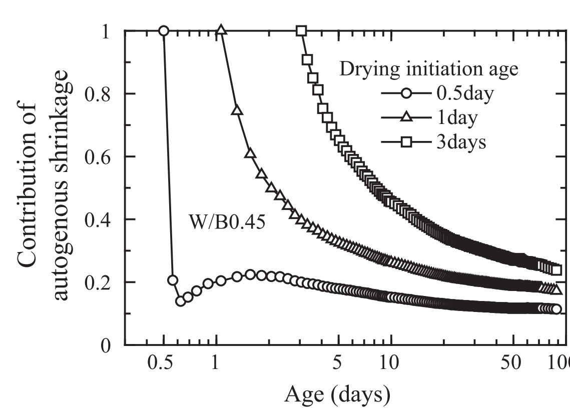

Fig. 18. Contribution of autogenous shrinkage (W/B0.45).

W/B is high. Considering the contribution of autogenous shrinkage strain at an age of 90 days when the contribution is almost constant, W/B affected the contribution strongly. Neglecting the influence of drying initiation age, the contribution in the case of W/B0.25, W/B0.35, and W/B0.45 is macroscopically about 50%, 30%, and 20%, respectively. The contribution of autogenous shrinkage strain increases when drying starts at a later age, and the influence of drying initiation age in the case of low W/B is more significant than in high W/B. Specifically, the differences in the contribution between a drying initiation age of 0.5 days and that of 3 days are 50% for W/B0.25, 30% for W/B0.35, and 15% for W/B0.45.

In the case of the high-strength concrete used in this study, even when it is exposed to drying conditions at an early age, about 70% of total shrinkage is contributed by autogenous shrinkage in the case of W/B0.25. With higher water–binder ratios, drying shrinkage is more dominant in the case of W/B0.35 than in the case of W/B0.45.

5. Conclusions

Based on BWC, this study quantitatively evaluated the autogenous shrinkage and drying shrinkage of high-strength concrete containing silica fume under drying conditions. The following conclusions can be drawn from the limited results:

(1) The drying initiation age affected BWC after drying. For water–binder ratios in the range 0.25–0.45 (compressive strength in the range 56.9–99.6 MPa), the earlier the drying initiation age and the higher the W/B are, the more significant the influence of drying initiation age is.
(2) The autogenous shrinkage strain of sealed concrete could be expressed in terms of BWC for a given W/B. A multinomial curve is applicable to describing the relationship between autogenous shrinkage strain and BWC in the case of concrete containing silica fume. For a given BWC, the lower the W/B is, the larger the autogenous shrinkage is.
(3) By evaluating hydration development based on BWC, autogenous shrinkage strain and drying shrinkage strain of concrete under drying conditions were separated from total shrinkage strain.
(4) Neglecting the influence of drying initiation age, the contribution of autogenous shrinkage strain under drying to total shrinkage was macroscopically about 50–20% based on the present method, while that was 70–30% based on the conventional SP. The latter resulted in overestimating autogenous shrinkage strain under drying conditions.

Drying shrinkage became dominant as W/B increased. The difference in the contribution of autogenous shrinkage between drying initiation at 0.5 days and at 3 days was 50–15%. The lower the W/B is, the larger the difference is.

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