# EVALUATION OF AUTOGENOUS SHRINKAGE AND DRYING SHRINKAGE BASED ON BOUND WATER CONTENT OF CEMENTITIOUS MATERIALS

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This study is aimed at quantitatively evaluating autogenous and drying shrinkage of high-strength concrete. To this end, the bound water content of concrete samples both sealed and exposed to drying is measured at different ages and the relationship between autogenous shrinkage strain and bound water content obtained for sealed concrete. Then, assuming that autogenous shrinkage strain depends only on bound water content even under drying conditions, the autogenous shrinkage strain for samples exposed to drying is estimated and drying shrinkage calculated. The calculations by this new method demonstrate that conventional calculations based on the superposition principle overestimate autogenous shrinkage strain under drying, while also giving the percentage contribution of autogenous shrinkage strain to total strain.

***Key Words :*** *high-strength concrete, blast furnace slag, bound water content, autogenous shrinkage, drying shrinkage*

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## 1. INTRODUCTION

Conventionally, it is common to consider that the main contributions to concrete volume change are thermal deformation caused by heat of hydration of the cement and drying shrinkage. However, it has been suggested that concretes with a low water-cement ratio and a large amount of binder, such as high-strength concrete and self-compacting concrete containing fine granulated blast furnace slag or silica fume, exhibit significant autogenous shrinkage due to hydration of the binder, with autogenous shrinkage linked closely to crack generation[1]. This suggestion led to an investigation of the influence of water-cement ratio, admixture type, and admixture replacement ratio on autogenous shrinkage[2], and recently, with such research becoming still more active, the prediction of autogenous shrinkage strain has also been attempted[3].

Almost all research so far has considered the autogenous shrinkage behavior of concrete without the exchange of moisture with the exterior environment. Even when drying has been considered, autogenous shrinkage and drying shrinkage were dealt with as independent phenomena, thereby making the inherent assumption that the principle of superposition was valid between autogenous shrinkage and drying shrinkage. Later, it was reported that the autogenous shrinkage behavior of concrete under drying conditions differs from that under sealed conditions, making the superposition principle inapplicable[4], [5], [6]. Additionally, research on the correlation between autogenous shrinkage and drying shrinkage, and the mechanism by which strain develops under their combined influence, has just started and has yet to provide sufficient elucidation. While this correlation has no important meaning in engineering practice (when autogenous shrinkage strain and drying shrinkage strain are used as input data to obtain restrained stress), it does become very important in predicting strain using to high accuracy using a microscopic approach.

The aim of this study was to clarify the autogenous shrinkage and drying shrinkage behavior of high-strength concrete under drying conditions, and the mechanism by which the resulting strain is generated. The first step was to quantitatively evaluate the hydration development of cementitious materials in high-strength concrete containing fine granulated blast furnace slag under drying conditions based on the bound water content. The parameters were water-binder ratio and age at the initiation of drying. Subsequently, autogenous shrinkage strain under drying conditions and drying shrinkage strain were separated from total shrinkage strain by establishing the relationship between bound water content, hydration index, and autogenous shrinkage strain. Based on the obtained results, the influence of both water-binder ratio and age at initiation of drying on autogenous shrinkage under drying were investigated. Finally, the applicability of the superposition principle was verified by comparing autogenous shrinkage strain under drying conditions and drying shrinkage strain as obtained using the described method with calculations using the superposition principle.

## 2. THE CONVENTIONAL APPROACH

### 2.1 Evaluation of hydration development under drying conditions

A lot of technical literature has considered the question of hydration development, since hydration determines all properties of cement paste, mortar, and concrete. Many researchers have proposed methods and models for estimating hydration development[7]. In most, however, attention focuses on the reaction rate at different stages of the hydration process without exchange of moisture with the exterior environment. In contrast, little research relates to hydration under drying conditions.

Given that hydration depends on the relative humidity within pores, Bazant[8] proposed an incremental formula for predicting the bound water content of concrete under drying conditions based on the relative rate of increase in bound water content. That is,

$$dw_n = \beta_T(h) f(w_n) dt \tag{1}$$

where, $dw_n$ : increment in bound water content during time interval $dt$

$\beta_T(h)$ : relative hydration rate (a function of relative humidity $h$ and temperature $T$ )

$f(w_n)$ : increment in bound water content during unit time under controlled conditions (e.g. relative humidity = 100%)

The fall in relative hydration rate due to drying is taken into account in Eq. (1), but no influence of drying on ultimate bound water content is considered. In fact, it is clear that drying not only induces a fall in hydration rate, but also leads to a reduction in ultimate bound water content; this is especially significant in the case of high-strength concrete, where the supply of water is restricted from the beginning due to the low water-binder ratio and further hydration is inhibited by the density of hydration products. For these reasons, Eq. (1) is inapplicable to high-strength concrete.

In view of practicability and simplicity, Nagamatsu[9] described the time dependence of bound water content under sealed condition as follows:

$$w_n = \frac{W_n t}{t + \dfrac{1}{a_s W_n}} \tag{2}$$

where, $w_n$ : bound water content at age $t$

$W_n$ : ultimate bound water content

$a_s$ : coefficient describing hydration rate

Furthermore, Nagamatsu formulated the relationship between degree of drying and the decrement in ultimate bound water content and proposed an equation for predicting the time-dependent bound water content of mortar under drying conditions as follows:

$$w_{nd} = w_{nk} + \frac{\Delta W_{nd}(t-k)}{(t-k) + \dfrac{1}{a_s \Delta W_{nd}}} \tag{3}$$

where, $w_{nd}$ : bound water content at age $t$ under drying conditions

$w_{nk}$ : bound water content at drying initiation age $k$, obtained using Eq. (2)

$\Delta W_{nd}$ : increment in bound water content from drying initiation age $k$ to the ultimate age

$$\Delta W_{nd} = W_{nd} - w_{nk}$$

$W_{nd}$ : ultimate bound water content under drying conditions

In Eq. (3), the influence of drying on ultimate bound water content is taken into account. However, it ignores the influence of drying on coefficient $a_s$, with $a_s$ depending only on W/C.

### 2.2 Autogenous shrinkage under drying conditions

The JCI technical committee on autogenous shrinkage research offers a definition of autogenous shrinkage that does not include volume change due to loss or ingress of substances, temperature variations, or application of an external force or restraint[10]. However, consideration should be given to the effect that water loss has on hydration, since autogenous shrinkage is a phenomenon resulting from the hydration of cement. Usually, moisture is exchanged with the exterior environment in concrete structures, and hydration is disturbed if drying takes place. Given the influence that drying has on hydration, it can be expected that autogenous shrinkage under drying conditions differs from that when sealed, especially in cases where the concrete undergoes drying at an early age.

Although a few researchers have reported on the autogenous shrinkage and drying shrinkage of concrete under drying conditions, most neglected to investigate the effects of drying on autogenous shrinkage[11], [12]. For convenience, they obtained drying shrinkage strain by subtracting autogenous shrinkage strain under sealed conditions from the total strain, considering autogenous shrinkage and drying shrinkage to be independent phenomena and assuming that the principle of superposition was applicable. However, in some cases, it was seen that drying shrinkage obtained using the principle of superposition would initially increase with time and then fall again, which is a meaningless result[6]. On the other hand, Ishida[5] integrated all volume change phenomena caused by drying shrinkage and autogenous shrinkage based on microscopic mechanisms, and then evaluated autogenous shrinkage and total shrinkage numerically under arbitrary conditions of environment, materials, mix proportion, and curing. As a result, Ishida was able to demonstrate that it is necessary to consider the interaction between hydration and water evaporation while properly estimating the shrinkage behavior under the influence of drying during the hydration process. The authors[5] themselves have evaluated the influence of drying on hydration development in high-strength concrete containing silica fume by measuring the bound water content, and indicated that autogenous shrinkage under drying will be overestimated and drying shrinkage underestimated if the principle of superposition is applied.

## 3. EVALUATION OF AUTOGENOUS SHRINKAGE STRAIN UNDER DRYING CONDITIONS

### 3.1 Evaluation of hydration development from bound water content

In this study, hydration development is evaluated according to essentially the same method as used by Nagamatsu. Time-dependent changes in bound water content under sealed conditions were estimated using Eq. (2).

Since the internal structure of hardened cement paste grows denser as hydration proceeds, resistance to the transport of moisture and ions through the hydrate layer gradually increases. Hence, the hydration of cement particles is disturbed and the hydration rate falls. In high-strength concrete, where formation of the internal structure is faster and the moisture content smaller than in normal concrete, hydration will be influenced by drying initiation age if the concrete is subjected to drying conditions at a relatively early age. It is reasonable to infer that the age when drying begins not only affects the ultimate bound water content but also the rate of increase in bound water content. Therefore, in this study, besides the influence of W/C on coefficient $a_s$ , the influence of drying initiation age is also considered in estimating the time-dependent change in bound water content under drying conditions.

Replacing coefficient $a_s$ with $a_d$ , which includes both influences in Eq. (3), Eq. (3) was used to estimate the hydration development of high-strength concrete under drying conditions, and Eq. (2) was used for the sealed case in this study.

As Eq. (2) and Eq. (3) indicate, the bound water content at age $t$ can be obtained from $W_n$ , $\Delta W_{nd}$ , $a_s$ , and $a_d$ . These values were determined using the method of least squares from measured values of $w_n$ and $w_{nd}$ .

### 3.2 Evaluation of autogenous shrinkage strain under drying conditions

The autogenous shrinkage of concrete, even under drying conditions, is influenced by the quantity and state of moisture in the concrete, as well as by the pore structure (pore distribution and porosity) [13], [14], [15], since it is caused by negative pressure resulting from self-desiccation as hydration proceeds. That is, it has a close relationship with bound water content. In concrete exposed to drying, the process of hydration is disturbed by the reduced water supply around cement particles, with the result that bound water content decreases simultaneously as drying shrinkage takes place. In this way, bound water content has a close relation with time-dependent changes in moisture content and pore structure, the driving force behind autogenous shrinkage. As shown in **Fig. 1**, the bound water content relates directly to the amount of hydrate present, and also reflects changes in moisture content due to hydration and drying.

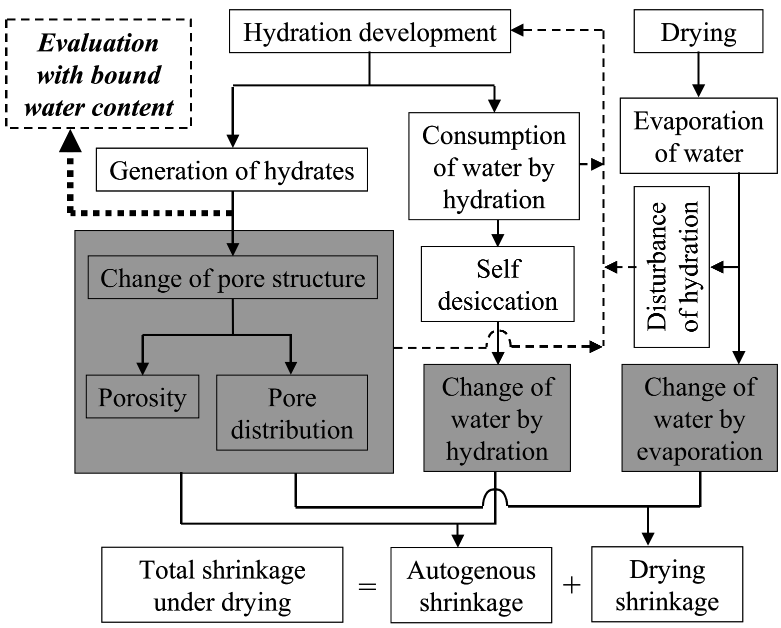

**Fig.1** Relation between autogenous shrinkage and bound water content

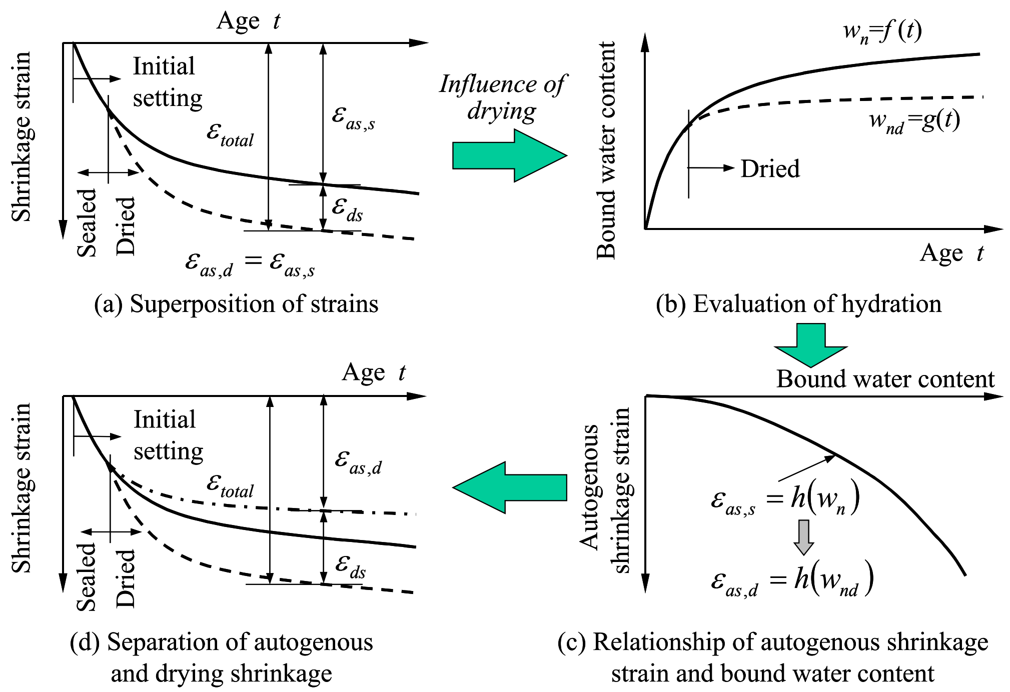


**Fig.2** Approach to evaluating autogenous shrinkage under drying and drying shrinkage

In this study, based on the above reasoning and remembering that bound water content can be measured directly at any given age, it is assumed that autogenous shrinkage is a function of bound water content only, even under drying conditions. This assumption means that bound water content corresponds in value to autogenous shrinkage whatever the curing conditions, since the same bound water content corresponds to the same quantity of hydrate. On the other hand, variations in age at initiation of drying cause variations in pore structure and result in different amounts of autogenous shrinkage. However, recent research[16] 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. This result could be considered as support for the above assumption, even though the materials and mix proportions used are different.

**Figure 2** illustrates the approach used in this study to evaluate autogenous shrinkage strain under drying conditions and drying shrinkage strain. The procedure is as follows:

(1) Measuring autogenous shrinkage strain $\varepsilon_{as,s}$, time-dependent bound water content $w_n$ under sealed conditions, total shrinkage strain $\varepsilon_{total}$, and bound water content $w_{nd}$ under drying conditions.

(2) Determining ultimate bound water content $W_n$, $\Delta W_{nd}$, and coefficients $a_s$ and $a_d$ in Eq. (2)and Eq. (3), based on measured values $w_n$, $w_{nd}$.

(3) Establishing the relationship $\varepsilon_{as,s} = h(w_n)$ between autogenous shrinkage strain $\varepsilon_{as,s}$ and bound water content $w_n$ under sealed conditions.

(4) Calculating autogenous shrinkage strain under drying $\varepsilon_{as,d}$ by applying this formulation under sealed conditions $\varepsilon_{as,s} = h(w_n)$ to that under drying conditions $\varepsilon_{as,d} = h(w_{nd})$.

(5) Calculating drying shrinkage strain $\varepsilon_{ds}$ by subtracting $\varepsilon_{as,d}$ from total shrinkage strain $\varepsilon_{total}$, according to **Fig. 2(d)**.

Using values of autogenous shrinkage strain and drying shrinkage strain obtained by the above procedure, the strain composition for different water-binder ratios W/B and different drying initiation ages is discussed.

## 4. EXPERIMENTAL PROGRAM

### 4.1 Materials and mix proportions

The materials and mix proportions of the high-strength concrete used in this study are shown in **Table 1**

**Table 2** Mix proportions

| No. | W/B (%) | BS/B (%) | s/a (%) | Unit content ($kg/m^3$) | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | W | C | BS | S | G | SP(xB) |
| C-BS25 | 25 | 50 | 41 | 160 | 320 | 320 | 664 | 973 | 0.95% |
| C-BS35 | 35 | 50 | 45 | 167 | 239 | 239 | 783 | 976 | 1.05% |
| C-BS45 | 45 | 50 | 47 | 170 | 189 | 189 | 854 | 978 | 1.00% |

B=C+BS; s/a: Percentage of fine aggregate by volume

**Table 1** Materials

| Material | Properties |
|---|---|
| Cement C | Ordinary Portland cement; Specific gravity: 3.14; Blaine: 3220 $cm^2/g$ |
| Blast furnace slag BS | Specific gravity: 2.90; Blaine: 6000$cm^2/g$ |
| 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 |

and **Table 2**; ordinary Portland cement and fine granulated blast furnace slag were used as binders.

4.2 Shrinkage

Specimens with a cross section of 100 x 100 mm and 400 mm in length were used for autogenous shrinkage and total shrinkage tests.

In order to deformation of the concrete free from restraint, friction between the concrete and the mold was made as low as possible according to “Test Method for Autogenous Shrinkage and Autogenous Expansion of Cement Paste, Mortar and Concrete” proposed by the JCI technical committee on autogenous shrinkage research[17]. Furthermore, in order to allow free thermal expansion of the concrete under the influence of cement hydration heat, foamed polystyrene sheets 2 mm in thickness were placed between the concrete and both mold ends. After casting, in order to prevent water evaporation, the molded specimens were covered with polyethylene film and wet fabric. Autogenous shrinkage specimens were demolded at the age of 1 day and then sealed with aluminum adhesive tape.

For total shrinkage specimens, the 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 bound water content test described later.

Shrinkage strain was measured by means of a strain gauge embedded in the center of each specimen along with a thermocouple. Autogenous shrinkage strain obtained by this method is considered to be an almost exact strain, since the temperature differential across the section is small (1 $^oC$ -2 $^oC$ ). Although a distribution of shrinkage strain occurs across the section after initiation of drying, this strain (which includes the influence of internal restrained stress due to the strain distribution within the section) equalizes, and it is the uniform strain that is measured with the embedded strain gauge.

Autogenous shrinkage strain was defined as any strain increment after initial setting. In this study, the initial setting times were about 0.38 days for W/B25%, 0.43 days for W/B 35%, and 0.56 days for W/B 45%, respectively.

Specimens for total shrinkage were dealt with as specimens for autogenous shrinkage before drying, and the aluminum adhesive tape was removed at initiation of drying. Drying was begun at 1 day, 3 days, and 7 days.

The climate conditions for all specimens were temperature 20 $\pm$ 1 $^oC$ and humidity 60 $\pm$ 5%. The shrinkage values given are averages for two specimens. There were no significant differences between each pair of specimens.

4.3 Bound Water Content

Measurements of bound water content are commonly made using cement paste. However, considering the objective of this study, which is to gain an understanding of autogenous shrinkage and drying shrinkage of concrete under drying conditions through an evaluation of hydration development, and given that the influence of drying differs in paste and in concrete, crushed material from a compressive test specimen was for measurements of bound water content. In order to obtain the same V/S as for the shrinkage test specimens, both ends of the compressive test specimen, which measured $\phi$ 100 x 200 mm, were sealed with aluminum adhesive tape even after drying.

After compressive testing at the specified age, both end sections of the specimen were cut off to a length of 50 mm. The remainder of the specimen was mixed and then crushed into particles of approximately 2.5 mm to 5 mm in size, so the obtained values of bound water content are the average value of a cross section. The mass of the sample used for measurement of bound water content was about 30 g. Immediately after measuring mass, the sample was repeatedly immersed in acetone to terminate the hydration reaction. After carrying out $105\,^{o}C$ furnace drying of the sample for 12 hours, it was heated to $600\,^{o}C$ in an electric furnace for 4 hours.

Bound water content was defined as the mass of water combined with a unit mass of the binder, and was calculated using Eq. (4). The mass of binder was determined by a method using hydrochloric acid solution. The bound water content values given are the average value of two samples obtained from different compressive test specimens.

$$w_n = \frac{W_{105} - W_{600}}{W_b} \times 100\% \tag{4}$$

where, $w_n$ : bound water content
$W_{105}$ : mass of sample after $105\,^{o}C$ drying
$W_{600}$ : mass of sample after $600\,^{o}C$ drying
$W_b$ : mass of binder

Bound water content was measured at the specified ages shown in **Table 3**. The intervals between these measuring ages are short at an early age since hydration proceeds quickly at an early age.

**Table 3** Age at bound water content measurement

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

## 5. RESULTS AND DISCUSSIONS

### 5.1 Autogenous shrinkage and total shrinkage

Time-dependent changes in autogenous shrinkage strain under sealed conditions are shown in **Fig. 3**.

This clearly shows that the thermal expansion coefficient of high-strength concrete is high at an early age[18]. However, in the case of $20\,^{o}C$ curing, the values of maximum temperature rise from initial temperature are $3.7\,^{o}C$ for W/B25%, $2.5\,^{o}C$ for W/B35% and $1.4\,^{o}C$ for W/B45%. These temperature rises caused by heat of hydration are small, and the contribution to strain of the thermal expansion coefficient is negligible. This being the case, the thermal expansion coefficient is assumed to have a constant value of $10\text{x}10^{-6}/^{o}C$ in this study, and autogenous shrinkage strain was obtained by subtracting the thermal strain based on this coefficient.

As **Fig. 3** makes clear, autogenous shrinkage strains developed rapidly at an early age but more slowly at a later age. After 60 days, autogenous shrinkage showed a tendency to converge. Comparing the case of W/B25%, in which autogenous shrinkage occurred just after setting, with cases such as W/B35% and W/B45%, slight expansion took place due to underestimation of thermal expansion.

A lower water-binder ratio results in greater autogenous shrinkage strain. In the case of W/B25%, the changes in autogenous shrinkage strain are $143\text{x}10^{-6}$ between the ages of 1 day and 3 days, or $94\text{x}10^{-6}$ between 3 and 7 days. Correspondingly, the changes are $94\text{x}10^{-6}$ and $75\text{x}10^{-6}$ for W/B35%, and $32\text{x}10^{-6}$ and $61\text{x}10^{-6}$ for W/B45%. As shown in **Fig. 4**, in which the change in autogenous shrinkage strain is expressed in terms of a strain rate, the lower the water-binder ratio, the larger the early-age strain rate. However, the

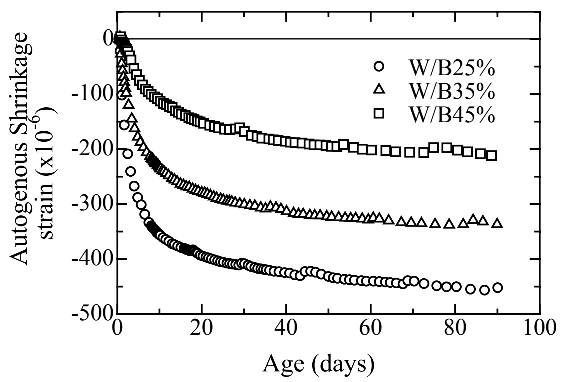


**Fig.3** Time-dependent change in autogenous shrinkage

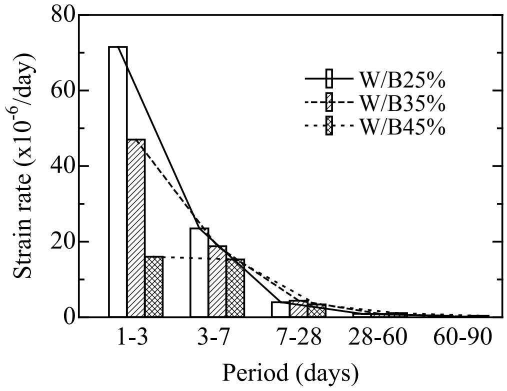


**Fig.4** Comparison of strain rate

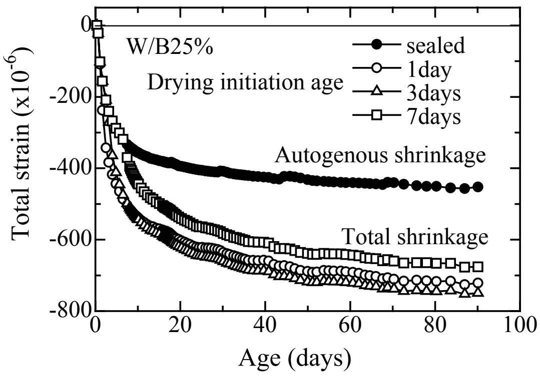


**Fig.5** Time-dependent change in total shrinkage strain (W/B25%)

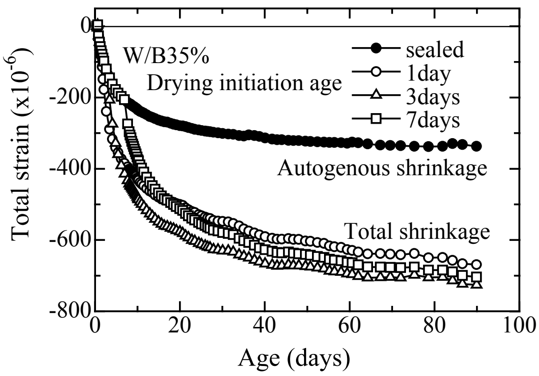


**Fig.6** Time-dependent change in total shrinkage strain (W/B35%)

differences in strain rate seen with different W/B values reduce over time, until after 7 days the rates are almost the same. The autogenous shrinkage strains in W/B45% and W/B35% at the age of 90 days are about $210 \times 10^{-6}$ and $340 \times 10^{-6}$, respectively. The autogenous shrinkage strain in W/B25% is more than twice as large as that in W/B45%, reaching a peak value of $450 \times 10^{-6}$.

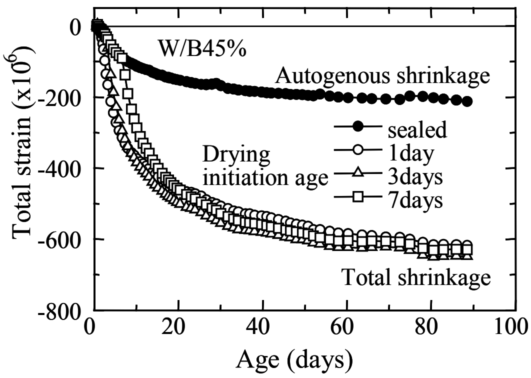


**Fig.7** Time-dependent change in total shrinkage strain (W/B45%)

The total shrinkage strains of concrete dried at different ages are shown in **Fig. 5** to **Fig. 7**. Autogenous shrinkage strains under sealed conditions are also indicated in these figures for comparison. Neglecting the influence of drying initiation age, and evaluating total shrinkage strain at the age of 90 days on average, the values of total shrinkage strain in W/B25%, W/B35%, and W/B45% are $715 \times 10^{-6}$, $700 \times 10^{-6}$, and $630 \times 10^{-6}$, respectively, and total shrinkage strain increases as W/B decreases. This demonstrates that total shrinkage is not dependent on unit water content, since a large amount of autogenous shrinkage occurs in low W/B concrete with a denser pore structure.

Furthermore, the figures show that the total shrinkage strain does not correlate exactly with drying initiation age. Concretely speaking, total shrinkage strains increase in order of drying initiation age 3, 1, and 7 days for W/B25%, 3, 7, and 1 days for W/B35% and 3, 7, and 1 days for W/B45%, respectively. Thus an earlier drying initiation age does not necessarily lead to greater shrinkage.

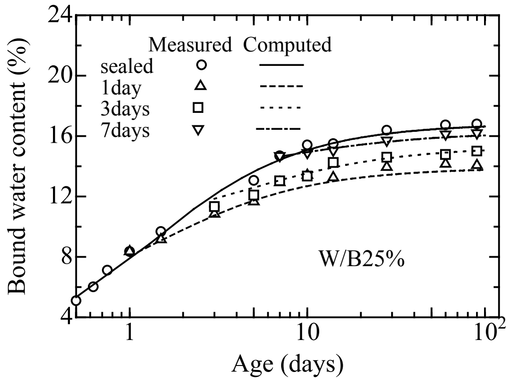


**Fig.8** Influence of drying initiation age on bound water content (W/B25%)

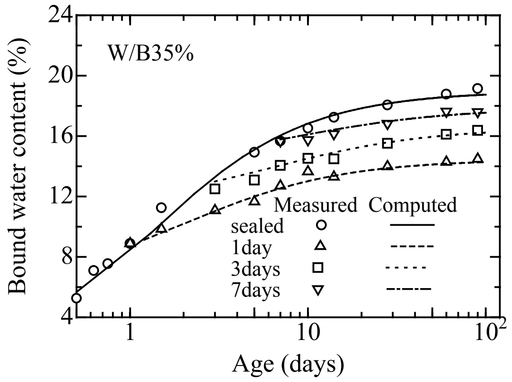


**Fig.9** Influence of drying initiation age on bound water content (W/B35%)

5.2 Hydration development of high-strength concrete under drying conditions

The time-dependent changes in measured bound water content of concrete with W/B25%, W/B35%, and W/B45% are shown in **Fig. 8**, **Fig. 9**, and **Fig. 10**, respectively.

The bound water content increased rapidly at an early age, but the rate of increase falls off in older concrete. After 28 days, it showed a tendency to converge. The lower the water-binder ratio is, the more notable this tendency is.

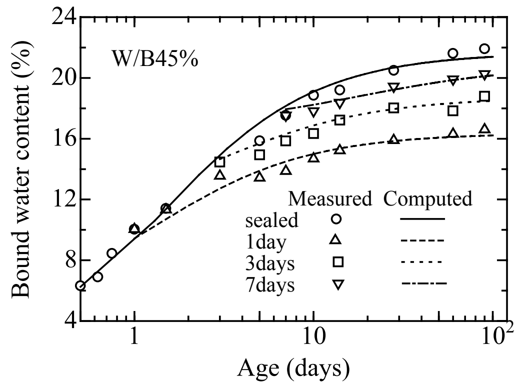


**Fig.10** Influence of drying initiation age on bound water content (W/B45%)

Although the variation in bound water content for different water-binder ratios is small at an early age, as the concrete ages, the bound water content drops more the lower the water-binder ratio is. For all water-binder ratios, binder hydration was disturbed when under drying conditions, and the bound water content 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 bound water content. In particular, in the case of W/B25%, the influence of drying on bound water content was very small when drying began at the age of 7 days. In the case of high-strength concrete made with silica fume, the effect of exposure to drying has been shown to be negligible when drying begins at the age of 3 days[5], in contrast with the concrete tested here. This difference between concrete types may be explained by the fact that concrete containing blast furnace slag hydrates more slowly than that containing silica fume.

Substituting the measured values of bound water content into Eq. (2) and Eq. (3) yields the ultimate bound water content $W_n$, the coefficient describing hydration rate under sealed conditions $a_s$, the increment in bound water content during drying increment $\Delta W_{nd}$, and the coefficient describing hydration rate under drying conditions $a_d$. These results are shown in **Fig. 11**, **Fig. 12**, and **Fig. 13**, respectively. In this study, the ultimate bound water content was 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.

As shown in **Fig. 11**, the ultimate bound water content under sealed conditions (without exchange of moisture with the exterior environment) increases almost linearly with increasing W/B. As Copeland[19] and Asaga[20] have pointed out, the hydration rate at the low rate stage is not dependent on W/B and tends toward a constant value, but at a late stage the space for hydrate generation decreases so the following hydration rate falls and the ultimate bound water content becomes small. The lower the value of W/B, the smaller the bound water content is. Corresponding to the reduction in ultimate bound water content, the coefficient describing hydration rate increased almost linearly.

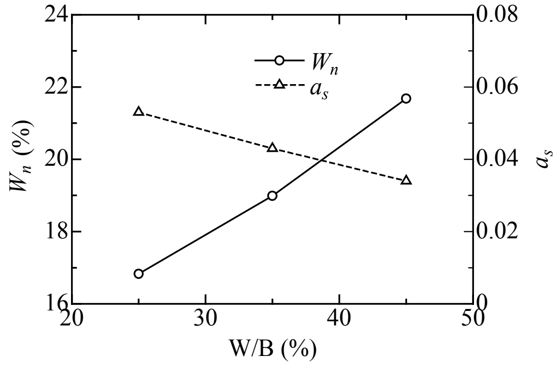


**Fig.11** Influence of W/B on $W_n$ and $a_s$ under sealing

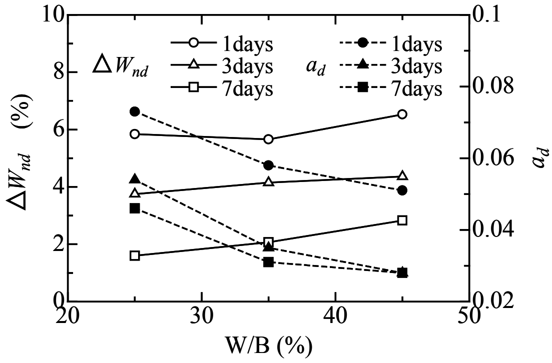


**Fig.12** Influence of W/B on $\Delta W_{nd}$ and $a_d$

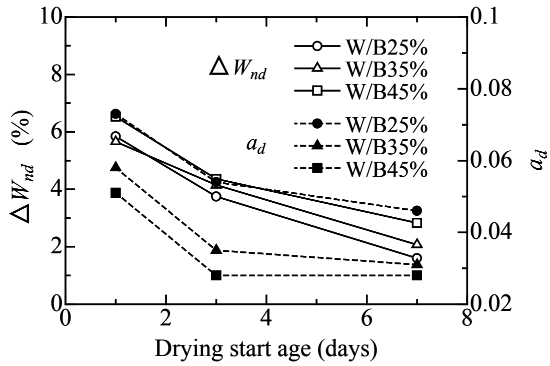


**Fig.13** Influence of drying initiation age on $\Delta W_{nd}$ and $a_d$

**Table 4** Coefficients

| No. | Drying start age (days) | W/B(%) | | |
|---|---|---|---|---|
| | | 25 | 35 | 45 |
| $W_n$ | Sealed | 16.83 | 18.99 | 21.68 |
| $a_s$ | Sealed | 0.053 | 0.043 | 0.034 |
| $\Delta W_{nd}$ | 1 | 5.84 | 5.66 | 6.53 |
| | 3 | 3.75 | 4.15 | 4.36 |
| | 7 | 1.60 | 2.07 | 2.83 |
| $a_d$ | 1 | 0.073 | 0.058 | 0.051 |
| | 3 | 0.054 | 0.035 | 0.028 |
| | 7 | 0.046 | 0.031 | 0.028 |

The influence of W/B on the increment in bound water content during drying period $\Delta W_{nd}$ was smaller than that under sealed conditions, as shown in **Fig. 12**. On the other hand, the later that drying begins, the smaller $\Delta W_{nd}$ is. This is because the supply of free water for hydration is restricted as a result of the advanced state of hydration when drying starts late.

**Figure 13** shows how the coefficient describing hydration rate under drying, $a_d$, decreases with W/B and drying initiation age, particularly when drying begins at the age of 1 day and 3 days. Trends in $W_n$, $a_s$, $\Delta W_{nd}$, and $a_d$ are summarized in **Table 4**. Using these values, the bound water content is computed using Eq. (2) and Eq. (3), with the results shown in **Fig. 8** to **Fig. 10** along with the measurement results. Based on these results, it can be concluded that the influence of drying initiation age should be taken into account when evaluating bound water content, at least in the case of high-strength concrete.

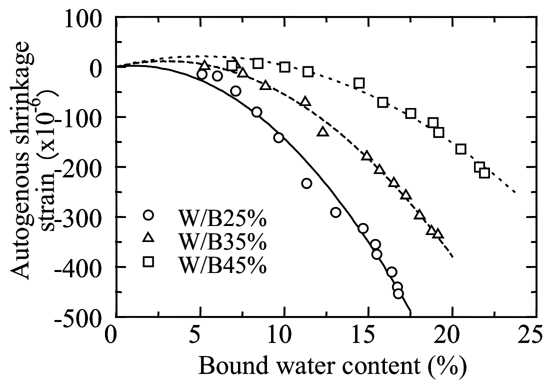


**Fig.14** Relationship of autogenous shrinkage strain and bound water content

5.3 Relationship between autogenous shrinkage strain and bound water content

The relationship between autogenous shrinkage strain under sealed conditions and bound water content is shown in **Fig. 14**. As this figure makes clear, autogenous shrinkage strain increases in line with bound water content, which in turn describes hydration development. However, almost no autogenous shrinkage strain arises initially, even if the bound water content increases. It is only after some time that autogenous shrinkage becomes prominent. Moreover, a high bound water content during this period of significant autogenous shrinkage corresponds to samples with large W/B. The low initial autogenous shrinkage might be explained by the restriction of original larger capillaries as hydration progresses, resulting in higher surface tension forces. The correspondence between high bound water content and W/B probably reflects the relatively coarse pore structure of concrete with a large W/B.

The relationship between autogenous shrinkage strain and bound water content shown in **Fig. 14** can be represented by the parabolic function shown in Eq. (5) except in the domain of low bound water content.

$$\varepsilon_{as,s} = aw_n^2 + bw_n \tag{5}$$

where, $a$, $b$ : constants depending on W/B. The values of these constants obtained by regression analysis are shown in **Table 5**.

**Table 5** Constant $a$, $b$

| W/B | 25% | 35% | 45% |
|---|---|---|---|
| $a$ | -1.80 | -1.34 | -0.79 |
| $b$ | 3.66 | 7.91 | 8.21 |

Having assumed autogenous shrinkage strain under drying to be a function of bound water content only, $\varepsilon_{as,d}$ can be obtained using Eq. (6).

$$\varepsilon_{as,d} = aw_{nd}^2 + bw_{nd} \tag{6}$$

where, $w_{nd}$ is obtained from Eq. (3).

Subtracting the autogenous shrinkage strain under drying conditions $\varepsilon_{as,d}$ obtained above from the total shrinkage strain $\varepsilon_{total}$, the drying shrinkage strain $\varepsilon_{ds}$ can be obtained as follows:

$$\varepsilon_{ds} = \varepsilon_{total} - \varepsilon_{as,d} \tag{7}$$

## 5.4 Evaluation of shrinkage strain

a) Separation of autogenous shrinkage from total shrinkage

It is necessary to separate total shrinkage into autogenous shrinkage and drying shrinkage in order to evaluate the shrinkage strain components of high-strength concrete under drying conditions. As noted in the introduction, these components can be separated by one of two methods. One is based on a superposition principle (SP) on the assumption that autogenous shrinkage under drying conditions is equal to that under sealing conditions. The other method is based on an evaluation of hydrate development by means of bound water content (BWC) considering the reduction in autogenous shrinkage due to drying. The components of shrinkage are shown in **Fig. 15** to **Fig. 17**. The autogenous shrinkage strain calculated by the SP method for drying conditions is an overestimate, as compared with that obtained by BWC. The discrepancy between SP and BWC results is evaluated here in terms of an overestimation ratio $\alpha$ defined in Eq. (8), in which shrinkage strains at the age of 90 days are used.

$$\alpha = \frac{\varepsilon_{sup} - \varepsilon_{pro}}{\varepsilon_{pro}} \times 100\% \tag{8}$$

where, $\varepsilon_{sup}$ : autogenous shrinkage obtained with SP
$\varepsilon_{pro}$ : autogenous shrinkage obtained with BWC

The overestimation ratios are about 49% for W/B25%, 98% for W/B35%, and 162% for W/B45% when drying was initiated at 1 day; the figures are 17%, 35%, and 106%, respectively, when drying was initiated at 3 days, and 14%, 24%, and 46% at 7 days.

For a given W/B, the earlier the initiation of drying occurs, the more significant the influence of drying is, and the larger the discrepancy in autogenous shrinkage strain obtained by the two evaluation methods. For a given age at initiation of drying, the larger W/B is, the more significant the influence of drying becomes, though the discrepancy in strain evaluations is less significant.

Based on the above results, it can be deduced that if concretes with W/B25% and W/B35% are exposed to

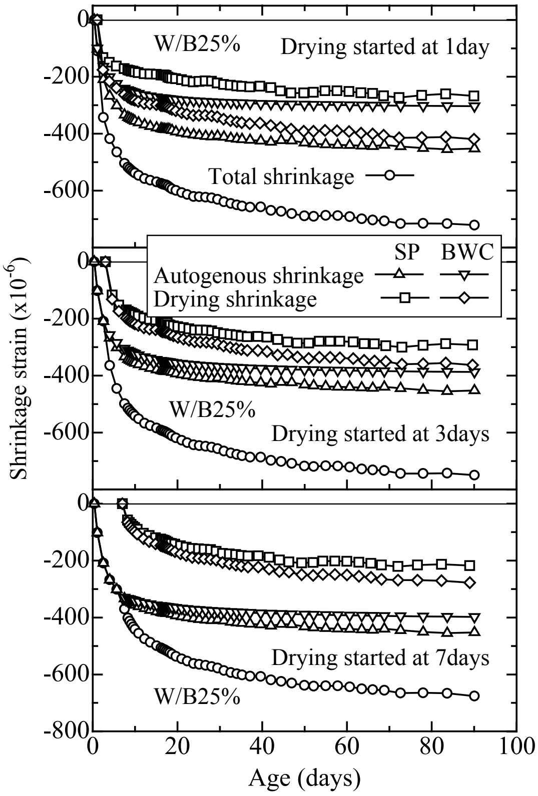


**Fig.15** Components of shrinkage (W/B25%)

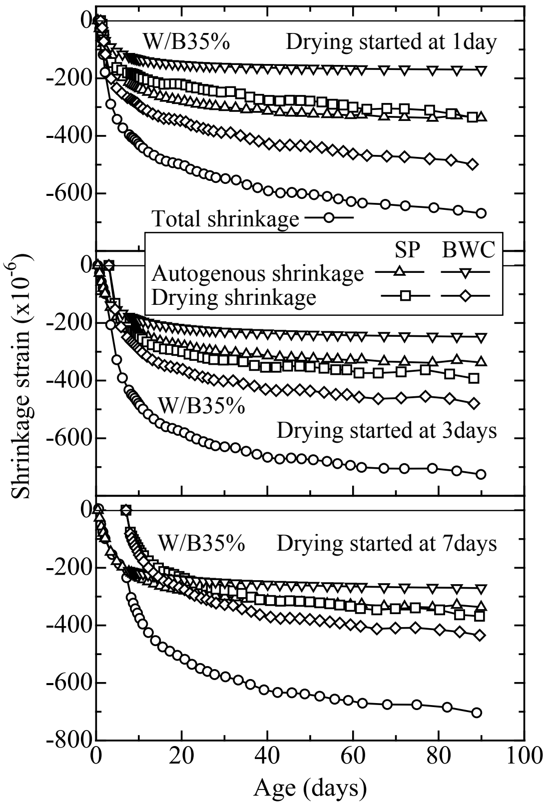


**Fig.16** Components of shrinkage (W/B35%)

drying conditions at the age of 3 days and at the age of 7 days, respectively, the overestimation ratio will be less than 25% when autogenous shrinkage strain under drying is taken to be the same as that under sealed conditions.

b) Proportion of autogenous shrinkage strain

Using Eq. (9), the contribution $\beta$ of autogenous shrinkage strain to total shrinkage is investigated, based on the results of the separation of strains obtained by BWC. **Figure 18** to **Fig. 20** show the time dependent changes in this contribution.

$$\beta = \frac{\varepsilon_{as,d}}{\varepsilon_{total}} \times 100\% \tag{9}$$

where, $\varepsilon_{as,d}$ , $\varepsilon_{total}$ : as defined in **Fig. 2(d)**

As shown in the figures, for any age at initiation of drying, the contribution made by autogenous shrinkage strain decreases with time as drying proceeds, and when W/B is high the fall is rapid. Considering the contribution made by autogenous shrinkage strain at the age of 90 days, by which time the contribution is almost constant, W/B affects the contribution strongly. Neglecting the influence of drying initiation age, the contribution in the case of W/B25%, W/B35%, and

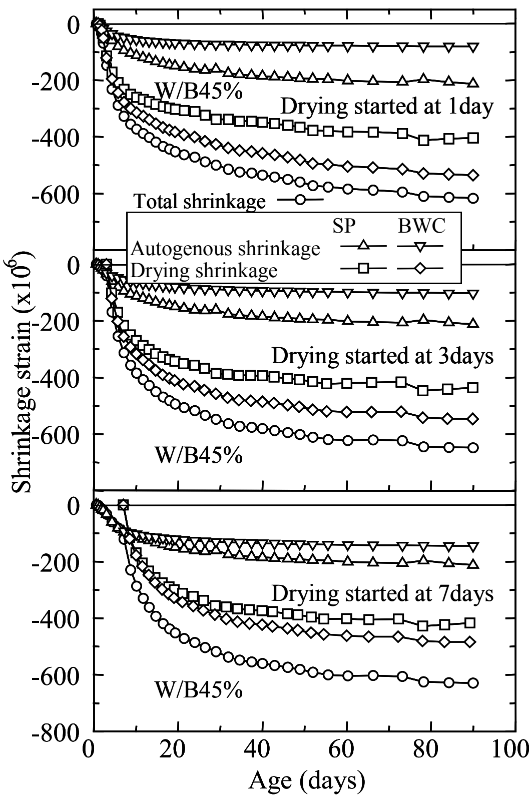


**Fig.17** Components of shrinkage (W/B45%)

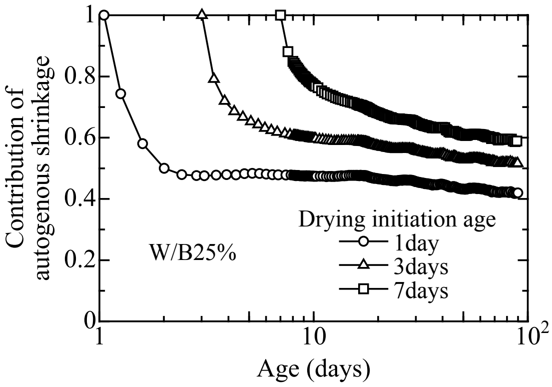


**Fig.18** Contribution of autogenous shrinkage (W/B25%)

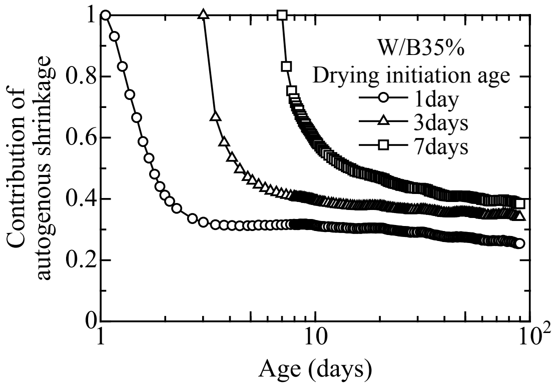


**Fig.19** Contribution of autogenous shrinkage (W/B35%)

W/B45% is macroscopically about 50%, 30%, and 20%, respectively. The contribution made by autogenous shrinkage strain increases somewhat if drying begins later, and the influence of drying initiation age in the case of low W/B is more significant than in the case of high W/B. Specifically, the difference in contribution between drying initiation age of 3 days and that of 7 days are 20% for W/B25%, 15% for W/B35%, and 10% for W/B45%.

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 half of total shrinkage is contributed by autogenous shrinkage in the case of W/B25%. With higher water-binder ratios, drying shrinkage becomes more dominant in the order W/B35% then W/B45%.

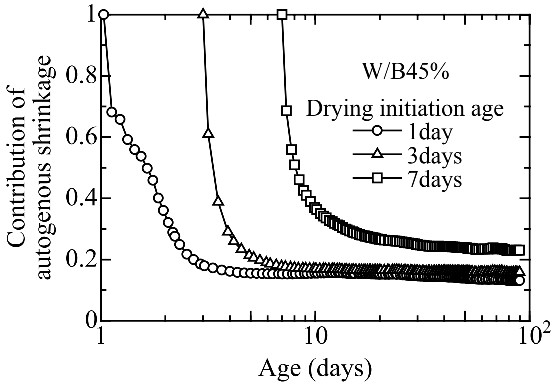


**Fig.20** Contribution of autogenous shrinkage (W/B45%)

## 6. CONCLUSIONS

Based on bound water content, An evaluation of autogenous shrinkage and drying shrinkage has been carried out for high-strength concrete under drying conditions. The concrete contained fine granulated blast furnace slag. The results were used to verify the applicability of the superposition principle (SP) by comparing autogenous shrinkage strain obtained using SP with the evaluations made in this study. The following conclusions can be drawn from the limited results presented here:

(1) The age at which drying is initiated affects the bound water content after drying. For water-binder ratios in the range 0.25 to 0.45, the earlier the initiation of drying and the higher the W/B is, the more significant the influence of drying initiation age.

(2) The existing prediction equation for bound water content was improved by taking the influence of drying initiation age into account when determining the coefficient describing hydration rate, and the validity of this improvement was verified.

(3) The autogenous shrinkage strain of sealed concrete can be expressed in terms of bound water content only for a given W/B. A parabolic curve has been matched to the relationship between autogenous shrinkage strain and bound water content, except in the domain of low bound water content. The lower the W/B is, the larger the autogenous shrinkage is, for a given bound water content.

(4) By evaluating hydration progress in terms of bound water content, the separate contributions of autogenous shrinkage strain and drying shrinkage strain to the total shrinkage strain of concrete under drying conditions were identified.

(5) The principle of superposition was found to overestimate autogenous shrinkage strain under drying conditions because it fails to take into account the influence of drying. The earlier the age at initiation of drying and the higher W/B is, the more significant the discrepancy is. However, in the case of concrete with W/B25% and W/B35% exposed to drying from the age of 3 days and 7 days, respectively, the overestimation ratio is less than 25%. In this case, autogenous shrinkage strain under drying conditions can be considered equal to that under sealed conditions in practice.

(6) Neglecting the influence of drying initiation age, the contribution of autogenous shrinkage strain under drying conditions to total shrinkage was, macroscopically, about 50% - 20%. Drying shrinkage became dominant as W/B increased. The difference in the contribution made by autogenous shrinkage between drying initiation at 3 days and at 7 days was 20% - 10%. The lower the W/B is, the larger the difference is.

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