Autogenous Shrinkage of Prestressed Self-Consolidating Concrete

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Abstract: Shrinkage can be critical factor for the design of structural members due to the length changes by the time-dependent deformation. Given the high fluidity and different mixture proportions of SCC, the shrinkage of such concrete can differ from those of conventional concrete or HPC of normal consistency. Proper estimate of autogenous shrinkage of self-consolidating concrete (SCC) can provide engineers with the information necessary for producing high quality products manufactured with SCC. An experimental program was undertaken to evaluate autogenous shrinkage of precast, prestressed SCC. Sixteen SCC with slump flow of 680 ± 20 mm were evaluated. These mixtures were made with 440 to 500 kg/m^3 of binder, Type MS cement or HE cement and 20% Class F fly ash, 0.34 to 0.40 *w/cm*, viscosity-modifying admixture content of 0 to 100 mL/100 kg of binder, and 0.46 to 0.54 sand-to-total aggregate volume ratio. Two high-performance concretes (HPC) with 0.34 and 0.38 *w/cm* and slump of 150 mm were also investigated. Based on the test results, the HPC developed similar autogenous shrinkage at 56 days compared to SCC made of a given binder type. Shrinkage was compared to prediction models proposed by Tawaza and Miyazawa 1997, Jonasson and Hedlund 2000, and CEB-FIP 1999. The Tazawa and Miyazawa model was modified to provide adequate prediction of autogenous shrinkage for precast, prestressed SCC.

Keywords: Autogenous shrinkage, self-consolidating concrete, prediction models, prestressed concrete.

1. INTRODUCTION

Given the high fluidity and different mixture proportions of SCC, the shrinkage of such concrete can differ from those of conventional concrete or HPC of normal consistency [1]. Autogenous shrinkage is the macroscopic volume reduction of cementitious materials when the cement hydrates after initial setting [2]. It is the consequence of withdrawal of water from the capillary pores by the hydration of the hitherto unhydrated cement. Autogenous shrinkage can be particularly high in mixtures made with relatively low *w/cm* and high content of cement and supplementary cementitious materials exhibiting high rate of pozzolanic reactivity at early age. In the case of SCC made with low *w/cm*, such as SCC used in precast, prestressed applications (typically 0.32 to 0.36), autogenous shrinkage develops rapidly because the water drained by the very fine porosity resulting from volumetric contraction is drained from capillaries that already have a small diameter. Moreover, once the hydration reaction starts, it develops at early age, so that water is drained rapidly from capillaries that are finer and finer, and therefore high tensile stresses are developed at early age, which results in the development of a high autogenous shrinkage [3]. Special attention is needed to minimize self-desiccation when using concrete with low *w/cm*.

For cement paste proportioned with high *w/cm*, the capillary porosity pressure is low and results in a low level of autogenous shrinkage [4]. SCC mixtures made with high *w/cm* (higher than 0.40) can exhibit relative low autogenous shrinkage. Hu and Barcelo [5] reported that, despite their higher paste volume, autogenous shrinkage of various SCC mixtures made with *w/cm* of 0.40 to 0.45 can be comparable to that of conventional concrete with 0.53 *w/cm*. This is mainly due to high *w/cm*. At an early age, such as from mixing to two days, autogenous shrinkage of the tested SCC mixtures was negligible but ranged between 50 and 200 microstrain after 200 days. Khayat and Morin [6] reported maximum autogenous shrinkage values ranging between 50 and 100 microstrain for SCC mixtures used in repair applications with 0.38 *w/cm*. Based on an analysis of a database of SCC mixture proportioning, Matthew *et al.* [7] reported that significant autogenous shrinkage can develop when the *w/cm* is reduced to 0.40 or lower.

Studies conducted by Song *et al.* [8] showed that, for SCC mixtures made with 0.34 *w/cm* and 40% replacements of cement by ground granulated blast furnace slag, the increase in the Blaine fineness of this slag from 4,000 to 6,000 or 8,000 cm^2/g resulted in greater autogenous shrinkage. After 28 days, both SCC made with 40% slag with Blaine fineness of 4,000 cm^2/g and that without any slag had similar autogenous shrinkage. These values considerably increased (about 2.5 folds) after 28 days when the Blaine fineness of the slag increased from 4,000 to 6,000 or 8,000 cm^2/g. The slag fineness also had significant effect on the rate of autogenous shrinkage for the first 28 days because finer slag particles have larger surface area exposed to the pozzolanic reaction. The faster the rate of reaction is, the greater the autogenous shrinkage is. Typical values of

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autogenous shrinkage of normal concrete, HPC, and SCC are summarized in Table **1**.

2. MIXTURE COMPOSITION

The mixture proportioning of the 16 SCC and two HPC mixtures of normal consistency used in this investigation are summarized in Table **2**. Four mixture proportioning parameters and one raw material parameter were considered in the experimental design. The initial slump flow of the SCC mixtures was 680 ± 20 mm.

3. AUTOGENOUS SHRINKAGE MEASUREMENTS

Using present standard testing methods, it is not possible to make any kind of reliable shrinkage measurements in the case of SCC. The beginning of hydration is essentially determined by the type of cement, and the amounts of superplasticizer used. Moreover, the lower the *w/cm* is, the higher the autogenous shrinkage is developed during the early-age (before 24 hours).

The measurement of autogenous shrinkage at an early age can be determined using the embedded vibrating wire strain gages. As presented in Fig. (**1**), a polystyrene sheet can be placed inside each plate of the mold so that free movements of the specimens are not restrained by the mold. Polyester film can be placed on the bottom of the mold, on the polystyrene sheet and on both sides of the mold so that specimens are not contacted directly with the mold and therefore the friction between the specimens and the mold can be reduced at maximum. After initial setting of the

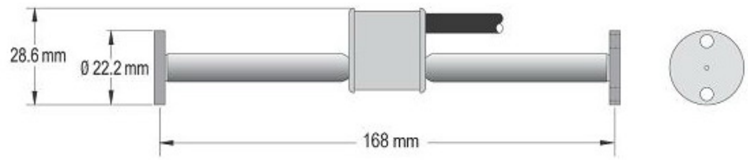
Table 1. Typical Autogenous Shrinkage Values of Concretes

Type of Concrete	Typically Values (10^{-6})	Observations
Normal concrete [ASTM 1940]	after one month: 40 after five years: 100	
HPC [RILEM TC 107-95]	700	*w/cm* = 0.17
SCC [JCI 1998]	100 to 400	• *w/cm* = 0.30 to 0.60; • unit powder content of 500 kg/m^3

Table 2. Mixture Compositions

	Mix No.	Binder kg/m^3	*w/cm*	VMA mL/100 kg CM*	Binder Type	S/A*** (%)
SCC (slump flow 680 ± 20 mm)	1	440	0.34	0	MS	0.54
	2	440	0.34	0	HE**	0.46
	3	440	0.34	100	MS	0.46
	4	440	0.34	100	HE	0.54
	5	440	0.40	0	MS	0.46
	6	440	0.40	0	HE	0.54
	7	440	0.40	100	MS	0.54
	8	440	0.40	100	HE	0.46
	9	500	0.34	0	MS	0.46
	10	500	0.34	0	HE	0.54
	11	500	0.34	100	MS	0.54
	12	500	0.34	100	HE	0.46
	13	500	0.40	0	MS	0.54
	14	500	0.40	0	HE	0.46
	15	500	0.40	100	MS	0.46
	16	500	0.40	100	HE	0.54
HPC	17	• *w/cm* = 0.34, Type MS cement, 12.5 mm crushed aggregate • Normal consistency mixtures with 150-mm slump				
	18	• *w/cm* = 0.38, Type HE + 20% Class F fly ash, 12.5 mm crushed aggregate • Normal consistency mixtures with 150-mm slump				

* CM = cementitious materials
** Type HE cement + 20% Class F fly ash
*** Crushed aggregate with MSA of 12.5 mm and natural sand



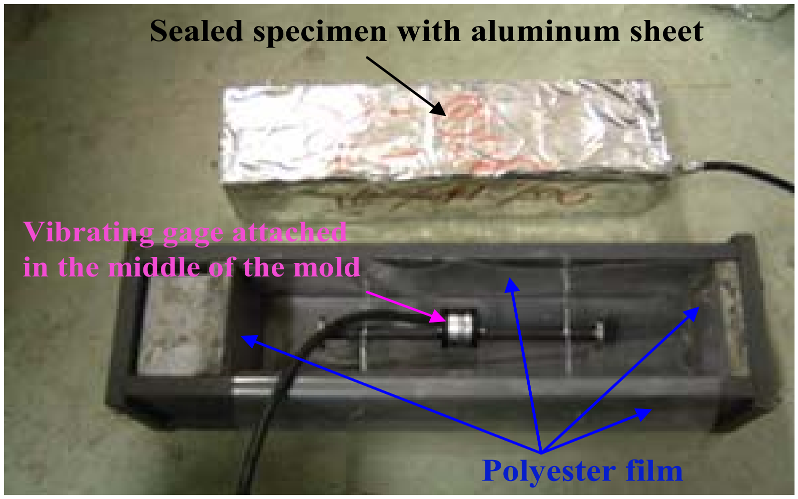


Fig. (1). Embedded vibrating wire gages (model EM-5) for determination of autogeneous shrinkage.

specimens, the deformation and thermal variation of the specimens can be monitored by the vibrating gage. A data acquisition system automatically registers the data from the vibrating gage. Autogenous shrinkage was measured on prisms 75 × 75 × 285 mm. The prisms were sealed immediately after removal from the molds at 18 hours of age and kept at 23 ± 2°C until the end of testing. Autogenous shrinkage was monitored until stabilization. The autogenous shrinkage was obtained by subtracting the total shrinkage from the thermal deformation. In order to apply the temperature correction to the strain gage readings, a linear thermal expansion coefficient of 11.5 µm/m/°C was used for the vibrating wire gages. On the other hand, the thermal expansion coefficient of the concrete was determined from the slope of the total deformation-temperature curve of concrete prisms subjected to control temperature changes. Two prisms were initially immersed in water at an approximate temperature of 50°C. Once the temperature of the samples is stabilized, the water is allowed to cool down to approximately 20°C. The resulting deformations are used to estimate the coefficient of the thermal expansion/ contraction of the concrete.

4. TEST RESULTS OF AUTOGENOUS SHRINKAGE

The shrinkage reached stable values after approximately two months of measurements and ranged from 100 to 350 microstrain. The highest autogenous shrinkage at 56 days was obtained for SCC No. 10 made with *w/cm* of 0.34, 500 kg/m^3 of binder, and Type HE cement with 20% of fly ash. Compared to SCC made with the same binder type, the two HPC mixtures exhibited similar autogenous shrinkage at 56 days of age. The lowest autogenous shrinkage at 28 and 56 days were obtained for SCC No. 5 made with *w/cm* of 0.40, Type MS cement, 440 kg/m^3 of binder, and 0.46 S/A.

As expected, *w/cm* had significant influence on autogenous shrinkage. Autogenous shrinkage of mixtures No. 1 to 4 and No. 5 to 8 made with binder content of 440 kg/m^3 are presented in Fig. (**2**). SCC made with *w/cm* of 0.34 exhibited relatively higher autogenous shrinkage values of 115 to 330 microstrain compared with 95 to 275 microstrain for SCC No. 5 to 8 proportioned with higher *w/cm* of 0.40. Similarly, mixtures No. 9 to 12 made with lower *w/cm* of 0.34 and binder content of 500 kg/m^3 exhibited higher autogenous shrinkage values of 165 to 345 microstrain compared with 105 to 210 microstrain for SCC No. 13 to 16 made with *w/cm* of 0.40 and same binder content, as illustrated in Fig. (**2**).

Binder type had considerable influence on autogenous shrinkage. SCC made with Type HE cement and 20% fly ash exhibited higher autogenous shrinkage compared to similar mixtures proportioned with Type MS cement, regardless of binder content, *w/cm*, S/A, and use of thickening-type VMA. For a given binder content of 440 kg/m^3, SCC mixtures No. 2, 4, 6, and 8 made with Type HE cement and 20% fly ash exhibited autogenous shrinkage values of 330, 280, 210, and 275 microstrain after 56 days of measurement, respectively, as illustrated in Fig. (**3**). The autogenous shrinkage values of SCC No. 1, 3, 5, and 7 were 115, 135, 95, and 100 microstrain, respectively. Similar results were found for SCC proportioned with 500 kg/m^3 of binder.

5. MODIFICATION OF EXISTING AUTOGENOUS SHRINKAGE PREDICTION MODEL

Autogenous shrinkage values of the 16 tested SCC and two HPC mixtures are compared to values predicted from the Tawaza and Miyazawa model 1997 [9], Jonasson and Hedlund model 2000 [10], and CEB-FIP model 1999 [11].

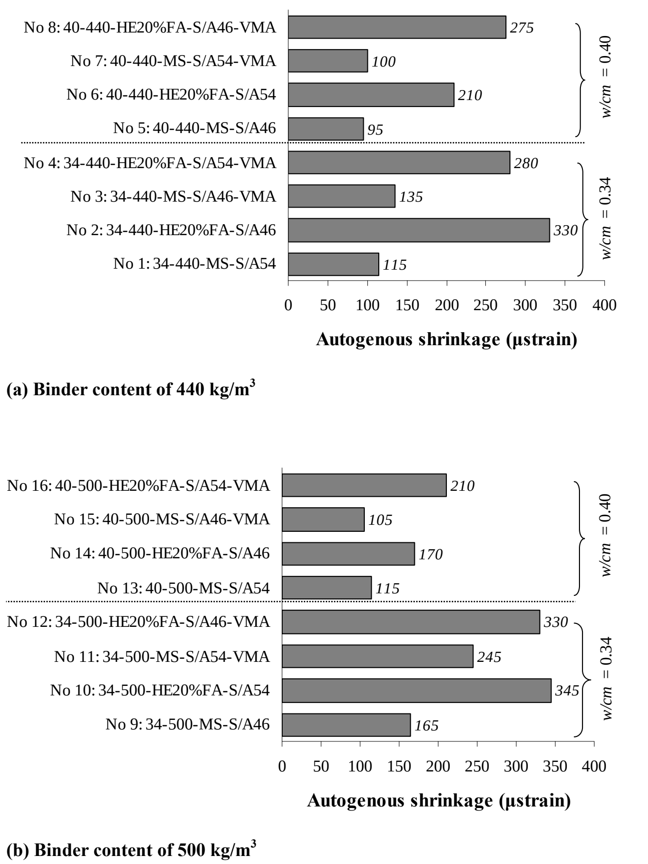


Fig. (2). Effect of *w/cm* on autogenous shrinkage after 56 days.

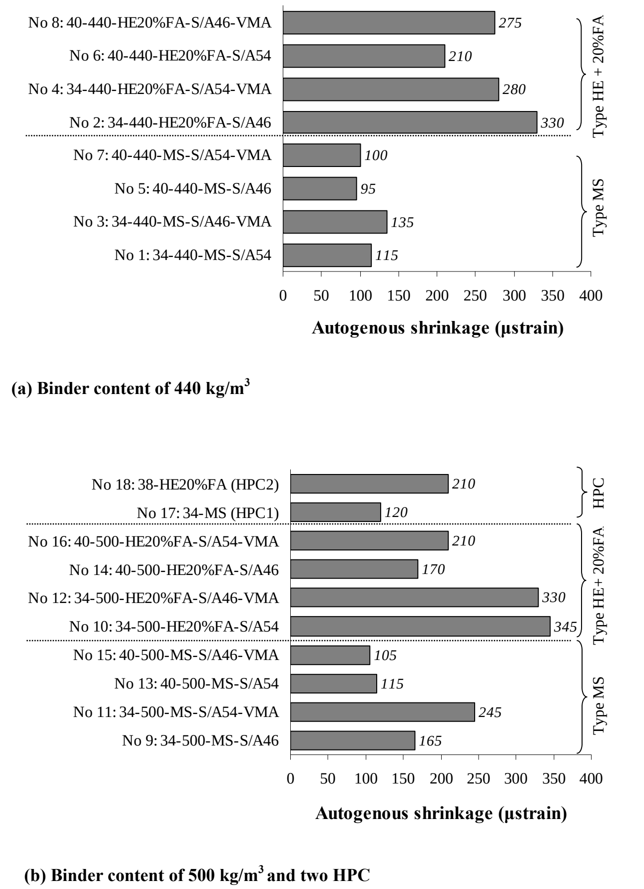


Fig. (3). Effect of binder type on autogenous shrinkage after 56 days.

The Tazawa and Miyazawa model is valid for concrete with W/B ranging from 0.20 to 0.56, and with normal volume concentration of aggregate, at an environmental temperature between 20 and 60°C. The Jonasson and Hedlund model is valid for concrete with W/B less than or equal to 0.40 and has compressive strength greater than or equal to 80 MPa. Unlike the Tazawa and Miyazawa and Jonasson and Hedlund models, the CEB-FIP 1999 model assumes that autogenous shrinkage of concrete is primarily dependent on its compressive strength. Detailed model descriptions can be found in Table **3**. Examples of autogenous shrinkage for mixtures No. 2 and No. 5 proportioned with different Type MS cement and Type HE cement with 20% of fly ash are compared to predicted values in Figs. (**4** and **5**), respectively. Moreover, in Fig. (**6**), autogenous shrinkage data of the 16 SCC mixtures determined between 1 and 56 days are compared to values predicted by the Tazawa and Miyazawa and CEB-FIP models.

The CEB-FIP 1999 and Jonasson and Hedlund 2000 models are shown to underestimate shrinkage at various ages and result in larger scattering compared with the Tazawa and Miyazawa model 1997. This is attributed to the fact that the CEB-FIP 1999 model assumes that autogenous shrinkage is largely dependent on compressive strength, and that the Jonasson and Hedlund model only considers W/B as the primary influencing factor for autogenous shrinkage. Unlike these two models, Tazawa and Miyazawa model takes into consideration of W/B and cement type as main input parameters of the model. Tazawa and Miyazawa model 1997 appears also to have large dispersion.

In order to improve the prediction accuracy, the cement type factor γ of Tazawa and Miyazawa prediction model was modified by applying the test data to the prediction model. The modified model for SCC designated for precast, prestressed applications can be expressed as Eq. 1:

$$\varepsilon_\infty(t) = \gamma \cdot \varepsilon_\infty(W/B) \cdot \beta(t) \quad (1)$$

in which: $\varepsilon_\infty(W/B) = 3070 \cdot \exp[-7.2(W/B)]$ *for* $0.2 \le W/B \le 0.5$

$\varepsilon_\infty(W/B) = 80$ *for* $0.5 < W/B$

$$\beta(t) = 1 - \exp[-a(t - t_0)^b]$$

where,

$\varepsilon_\infty(t)$ = autogenous shrinkage at the time of t (microstrain);

t = age (day);

t_0 = initial setting time (day);

γ = cement factor, 0.56 for Type MS cement; 1.18 for Type HE + 20% FA binder, and

a and b = constants depend on W/B are given in Table **4**.

Table 3. Summary of Various Models for Autogenous Shrinkage

<table>
<tr><th></th><th>Prediction Models</th></tr>
<tr><td>Tazawa and Miyazawa 1997</td><td>

$$\varepsilon_{\infty}(t) = \gamma \cdot \varepsilon_{\infty}(W/B) \cdot \beta(t)$$

In which, $\varepsilon_{\infty}(W/B) = 3070 \cdot \exp[-7.2(W/B)] \quad for\ 0.2 \le W/B \le 0.5$

$\varepsilon_{\infty}(W/B) = 80 \quad for\ 0.5 < W/B$

$$\beta(t) = 1 - \exp[-a(t - t_0)^b]$$

where, t is age in days; t_0 is the initial setting time in days; γ is 1.0 for ordinal Portland cement (OPC) and 0.6 for belite cement; the constants, a and b, which are dependent on W/B are given in Table 4.
</td></tr>
<tr><td>CEB-FIP 1999</td><td>

$$\varepsilon_{as}(t) = \alpha_{as}\left(\frac{f_c^{'}(t)/10}{6 + f_c^{'}(t)/10}\right)^{2.5} \cdot [1 - \exp(-0.2\sqrt{t})]$$

where, $f_c^{'}$ is compressive strength in MPa at the age of t, α_{as} is a coefficient, which depends on the type of cement, and t is age of concrete in days.

<table>
<tr><td>Type of cement</td><td>α_{as}</td></tr>
<tr><td>Slowly hardening cements</td><td>800</td></tr>
<tr><td>Normal or rapidly hardening cements</td><td>700</td></tr>
<tr><td>Rapidly hardening high-strength cements</td><td>600</td></tr>
</table>
</td></tr>
<tr><td>Jonasson and Hedlund 2000</td><td>

$$\varepsilon_{as}(t) = [-0.65 + 1.3(W/B)] \cdot 10^{-3} \cdot \exp\left[-\left(\frac{5}{t - t_{start}}\right)^{0.3}\right]$$

where, t_{start} is 1 day as start time of autogenous shrinkage starts.
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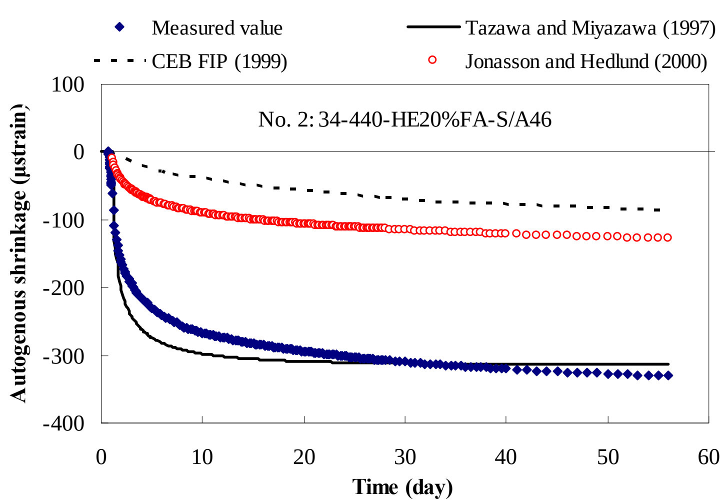


Fig. (4). Comparison of autogenous shrinkage of SCC No. 2 to values predicted by different models.

6. VERIFICATION OF THE MODIFIED MODEL

The comparison between measured and predicted autogenous shrinkage for the original and modified Tazawa and Miyazawa models at various ages are shown in Fig. (**7**). The slope (A of the y = A*x equation) of the y vs. x values (i.e. predicted vs. measured strengths) reflects the degree of

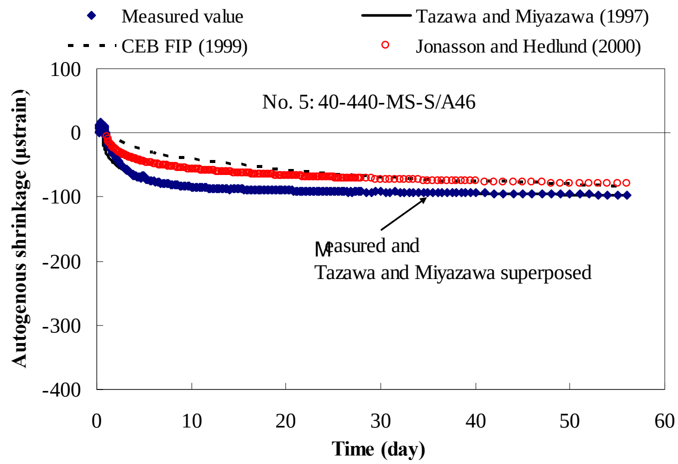
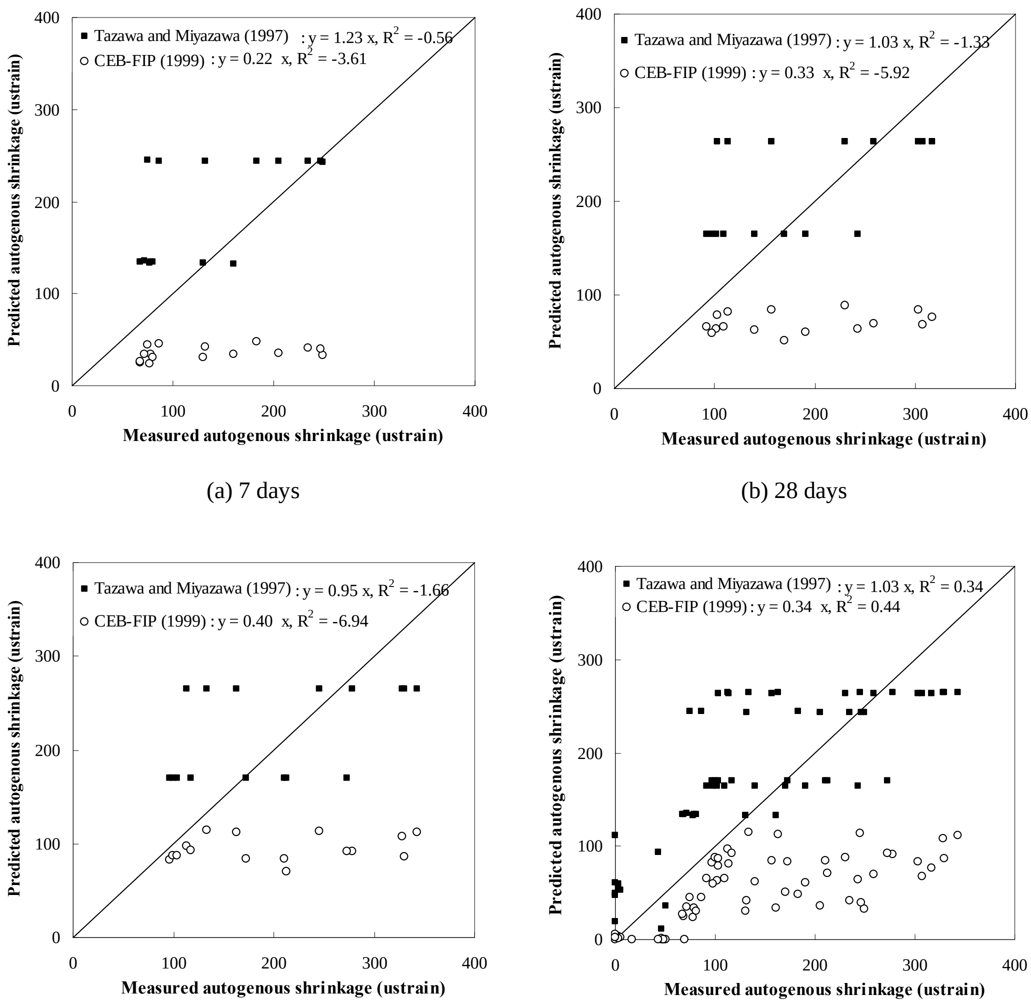


Fig. (5). Comparison of autogenous shrinkage of SCC No. 5 to values predicted by different models.



(a) 7 days

(b) 28 days

(c) 56 days

(d) at various days (1, 7, 14, 28, and 56 days)

Fig. (6). Comparison of measured and predicted autogenous shrinkage values of 16 SCC mixtures.

accuracy of the prediction equation to the measured data. The R^2 values indicate the degree of scattering of the predicted-to-measured strength data to the y = A*x values. The A and R^2 values of the modified model are significantly higher than those of the original model at various ages. As indicated in Fig. (**7**), A and R^2 values improved from 1.03 to 1.00 and from 0.34 to 0.83, respectively.

Table 4. Constants, a and b

W/B	0.20	0.30	0.40	0.50	0.60
a	1.2	1.5	0.6	0.1	0.03
b	0.4	0.4	0.5	0.7	0.8

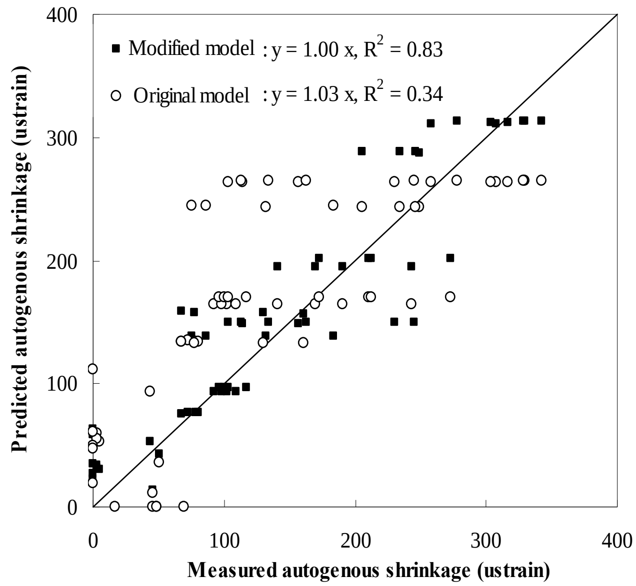


Fig. (7). Comparison of measured and predicted autogenous shrinkage from original and modified Tazawa and Miyazawa models at various days (1, 7, 14, 28, and 56 days).

7. CONCLUSIONS

Based on the test results of the experimental program and the comparisons among three autogenous shrinkage prediction models, the following conclusions can be drawn for SCC proportioned for precast, prestressed structural applications:

- Autogenous shrinkage is highly affected by *w/cm* and binder content. In addition, SCC made with Type HE cement with 20% fly ash (Class F) can develop higher autogenous shrinkage compared to that with Type MS cement.
- Autogenous shrinkage reaches stable values after 56 days of measurements and can vary between 100 and 350 microstrain, depending on the mixture composition. The majority of autogenous shrinkage occurs in the first 28 days, and reaches about 85% to 95% of ultimate values at 56 days.
- Compared to SCC made of a given binder type, the two HPC mixtures exhibits similar autogenous shrinkage at 56 days.
- The CEB-FIP 1999 and Jonasson and Hedlund 2000 models are shown to underestimate shrinkage at various ages and result in larger scattering compared with the Tazawa and Miyazawa's model 1997.
- The Tazawa and Miyazawa 1997 model with suggested modification for a cement factor can be used to estimate autogenous shrinkage of SCC designated for precast, prestressed structural applications.

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