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ESTIMATION OF AUTOGENOUS SHRINKAGE OF CONCRETE

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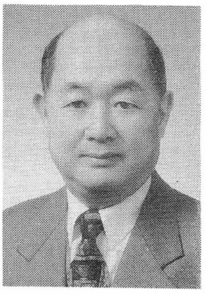

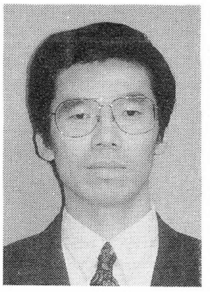

Ei-ichi TAZAWA Shingo MIYAZAWA

Various factors influencing autogenous shrinkage of concrete are summarized by reviewing previous studies. A prediction model for autogenous shrinkage of concrete, in which it is treated as a function of the type of cement and pozzolan, water-binder ratio, and effective age, is proposed based on experimental data. The accuracy of the model is evaluated using existing experimental results.

Key Words *:autogenous shrinkage, prediction, type of cement, water-cement ratio, temperature*

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1. INTRODUCTION

It has been proved in recent studies that autogenous shrinkage of concrete due to cement hydration is particularly significant for high-strength concrete[1][2]. It has also been demonstrated that autogenous shrinkage should be taken into account in the crack control and design of high-strength concrete structures. For example, the autogenous shrinkage stress due to restraint by embedded reinforcing bars can be very large[3]. When high-strength concrete is used for structures with large members, not only must thermal stress due to cement hydration be taken into account but also autogenous shrinkage stress[4]. Autogenous shrinkage also affects prestress loss with time and statically indeterminate force.

A prediction equation for estimating the shrinkage strain of normal strength concrete has been proposed by the Japan Society of Civil Engineers (JSCE)[5]. The shrinkage strain as calculated with the JSCE equation, which includes autogenous shrinkage strain, is a function of water content and the ratio of surface area to volume of a member, because it has been derived under conditions in which drying shrinkage is dominant. However, autogenous shrinkage occurs even in concrete without evaporation, and is significantly influenced by the water-cement ratio rather than water content. Further, cement type has great influence on autogenous shrinkage, whereas this is not the case in drying shrinkage. Therefore it is important to establish a prediction equation for autogenous shrinkage strain in order to estimate the shrinkage strain of high-strength concrete.

In this study, various factors influencing autogenous shrinkage are summarized with the aim of introducing a prediction equation. A prediction equation is proposed, on the basis of experimental data, for concrete with a wide range of water-cement ratios, and predicted values are compared with experimental data given in previous reports by other researchers.

2. PREVIOUS STUDIES

A number of researchers have recently been studying the factors that influence autogenous shrinkage, which include cement type, admixture type and dosage, mix proportion, and concrete temperature. These works are summarized in Chapter 3. However, little research has been done on the prediction of autogenous shrinkage strain. A prediction equation for the autogenous shrinkage of cement paste, which is a function of the mineral composition of the cement, has been proposed by the authors[6][7]. But this cannot be applied to a wide range of water-cement ratios and the degree of hydration cannot be easily determined. Several prediction equations have also proposed by researchers in Europe. It has been reported by Larrard[8] that the ultimate autogenous shrinkage strain can be predicted by a function of water-cement ratio and the replacement ratio of silica fume. But autogenous shrinkage before one day of age, which can be quite large for concrete with a low water-cement ratio, cannot be obtained by this equation.

The following equations for predicting autogenous shrinkage have been proposed by the French Chapter of RELEM (AFREM) for the purpose of designing prestressed concrete structures[9].

For t<28days:

$$\varepsilon_{as}(t, f_{c28})=0 \qquad :f_c(t)/f_{c28}<0.1 \tag{1}$$

$$\varepsilon_{as}(t, f_{c28})=(f_{c28}-20)\{2.2f_c(t)/f_{c28}-0.2\}10^{-6} \qquad :f_c(t)/f_{c28}\geqq 0.1 \tag{2}$$

For t≧28days:

$$\varepsilon_{as}(t, f_{c28})=(f_{c28}-20)\{2.8-1.1\exp(-t/96)\}10^{-6} \tag{3}$$

where,

$\varepsilon_{as}(t, f_{c28})$ is autogenous shrinkage from the initial setting time to a certain age t

f_{c28} is compressive strength at 28 days

$f_c(t)$ is compressive strength at a certain age t

If $f_c(t)$ is unknown, it may be obtained with the equation, $f_c(t)=\{t/(1.40+0.95t)\}f_{c28}$, where t is age in days.

In this model, it is assumed that the autogenous shrinkage before 28 days is related to the degree of hydration and is a function of $f_c(t)/f_{c28}$ (see eq.(2)), and that autogenous shrinkage after the age of 28 days is a function of time (see eq.(3). It is also assumed that autogenous shrinkage does not occur before the age corresponding to $f_c(t)/f_{c28}=0.1$(see eq.(1)). As there are few practical prediction equations except the AFREM model, the applicability of the model is also investigated.

3. FACTORS INFLUENCING AUTOGENOUS SHRINKAGE

3.1 Influence of cement and mineral admixture types

Autogenous shrinkage of concrete is strongly dependent on the type of cement. Medium-heat Portland cement and belite-rich cement result in lower autogenous shrinkage than ordinary Portland cement. It has been demonstrated by the authors that the effect of a cement's mineral composition is much larger than that on drying shrinkage[10]. It has been also reported that autogenous shrinkage is increased by using silica fume and blast furnace slag with high specific surface areas, and that it is slightly decreased if fly ash is used[11][12]. Therefore, the influence of the type of cement as well as type and content of any mineral admixtures should be taken into account in predicting autogenous shrinkage.

3.2 Influence of volume concentration of aggregate

Since autogenous shrinkage occurs in the cement paste phase, it is reduced as the volume concentration of aggregate increases. It has been reported that the effect of volume concentration of aggregate can be estimated using an existing composite model in which concrete is assumed to be a two-phase material consisting of cement paste and aggregate[13]. As the unit water content of concrete generally ranges from 150 to 170 kg/m^3, the volume concentration of aggregate generally ranges form 0.55 to 0.60 for concrete with a water-cement ratio of 0.2, and 0.69 to 0.72 for concrete with a water-cement ratio of 0.4. A difference in volume of aggregate results in only a 5% variation in autogenous shrinkage strain at most when the composite model is used for the estimate. Thus, variations in aggregate volume concentration can be neglected without significant error in estimating autogenous shrinkage for normal aggregate proportions.

3.3 Influence of water-cement ratio

The influence of water-cement ratio on autogenous shrinkage of concrete is shown in Fig.1. It can be seen that the ultimate value of autogenous shrinkage increases with decreasing water-cement ratio. Further, autogenous shrinkage of concrete with a low water-cement ratio increases more rapidly and reaches its ultimate value at an earlier age than that of concrete with a high water-cement ratio. Thus, water-cement ratio is a more important factor in estimating autogenous shrinkage of concrete with normal volume concentrations of aggregate than water content and cement paste content.

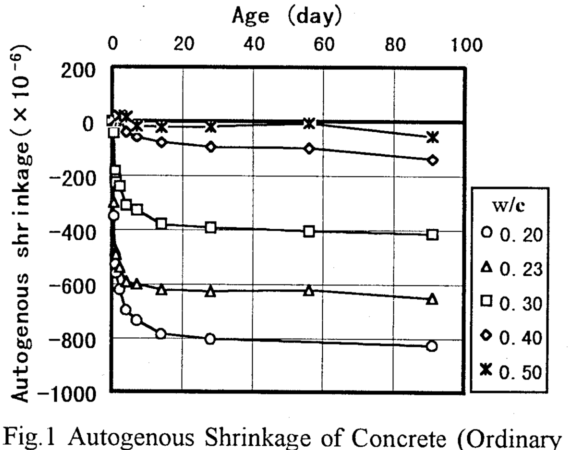

Fig.1 Autogenous Shrinkage of Concrete (Ordinary Portland Cement)

3.4 Influence of superplasticizer

A superplasticizer is generally used in high-strength concrete with a low water-cement ratio. It has been reported that autogenous shrinkage at later ages is slightly reduced if naphthalene type, polycarboxylic acid type, or aromatic aminosulfonate type of superplasticizers are used[12]. However, the difference is very small. Delayed setting due to a large dosage of superplasticizer and /or due to using a retardant type of plasticizer results in a delayed initiation of autogenous shrinkage. Therefore, in order to predict autogenous shrinkage at an early age with precision, the equation should be a function of elapsed time after setting.

3.5 Influence of concrete temperature

It has been proved that the rate of autogenous shrinkage at an early age increases with increasing concrete temperature, while at later age, like 3 months, it is not notably influenced by the temperature[4]. In this study, the effective age as proposed by the CEB-FIP model code[14] is used to take into account the effect of temperature on the rate of autogenous shrinkage.

3.6 Influence of specimen size

There has been no clarification of how autogenous shrinkage is influenced by the size of a concrete member. However, it has been seen that autogenous shrinkage at an early age increases with specimen size, as explained by the temperature effect previously mentioned, but that the ultimate value is not considerably influenced by specimen size[15]. It is thought that size effect can be considered a temperature effect, allowing the size effect itself to be neglected.

4. EXPERIMENTAL PROCEDURE

4.1 Materials and mix proportion

Ordinary Portland cement (N), moderate-heat Portland cement (M) and low-heat cement with a high C_2S content (L) were used. The mineral composition of the cements is shown in Table 1. River sand (specific gravity: 2.60; absorption: 1.76 %; fineness modulus: 3.15) was used as the fine aggregate and gravel (specific gravity:

Table 1 Mineral Composition of cement(%)

Type	C_3S	C_2S	C_3A	C_4AF	$CaSO_4$	total
N	64.9	11.0	7.1	8.2	3.9	95.1
M	50.8	29.5	0.9	12.8	3.2	97.2
L	22.4	57.8	3.3	9.7	4.1	97.3

Table 2 Mix Proportion and Properties of Flesh Concrete

Type of Cement	w/c	s/a (%)	Unit content (kg/m^3)				ad. (%)	Aggregate volume fraction	air (%)	Slump (slump flow) (cm)	Initial setting (hour)	Reference number
			W	C	S	G						
N	20.0	30	160	800	434	1070	1.6	0.556	2.1	4.5	3.8	
	20.0	31	160	800	452	1044	0.6	0.567	3.3	(56.0x55.0)	-	11
	23.0	32	160	696	498	1120	1.3	0.599	1.7	8.5	4.5	
	28.1	40	160	569	645	997	2.45	0.620	2.5	(57.5x56.5)	9.0	16
	30.0	37	165	550	606	1092	1.0	0.630	2.0	17.5	7.0	
	30.0	37	170	567	590	1044	0.2	0.621	3.0	19.5	-	11
	31.4	43	160	510	714	976	2.2	0.639	2.0	(60.5x58.5)	10.3	16
	40.0	40	170	425	671	1064	0.04	0.645	4.7	5.0	-	
	40.0	40	180	450	655	1021	0.6	0.637	4.1	12.5	-	11
	50.0	43	170	340	752	958	0.03	0.638	5.4	15.0	6.7	
	56.0	46	160	286	850	1025	0.25	0.709	2.9	6.5	9.0	16
M	23.0	32	160	696	498	1120	1.3	0.599	0.3	(80.0x78.0)	4.2	
	30.0	37	165	550	611	1097	1.0	0.630	2.0	(57.0x56.0)	7.9	
L	23.0	32	160	696	498	1120	1.3	0.599	0.6	(74.5x71.0)	5.2	
	27.6	40	160	580	645	997	1.9	0.620	4.0	(59.0x58.5)	9.0	16
	30.0	37	165	550	611	1097	1.0	0.630	3.7	(67.0x65.0)	9.0	
	30.0	34	160	533	633	1120	1.0	0.656	1.9	7.0	-	4
	38.0	47	160	421	818	951	1.7	0.669	2.3	(60.5x59.0)	6.0	16
	65.0	48	156	240	902	1025	0.25	0.729	3.5	7.0	-	16

2.75; absorption: 1.26 %; maximum size: 25 mm) was used as the cause aggregate. A polycarboxylic acid superplasticizer was used for concretes with water-cement ratios ranging from 0.20 to 0.30 and a resin air entraining agent was used for concretes with ratios of 0.40 and 0.50. The mix proportion of the concretes, the properties of fresh concrete, and the initial setting time are shown in Table 2. Mix proportions marked with a reference are from previous experiments by the authors. In the previous studies, the test method used for autogenous shrinkage was the same as that in this study, although the lots of the cements and the kinds of the aggregates were different. The data in the previous studies are used to study the applicability of the prediction equation for autogenous shrinkage.

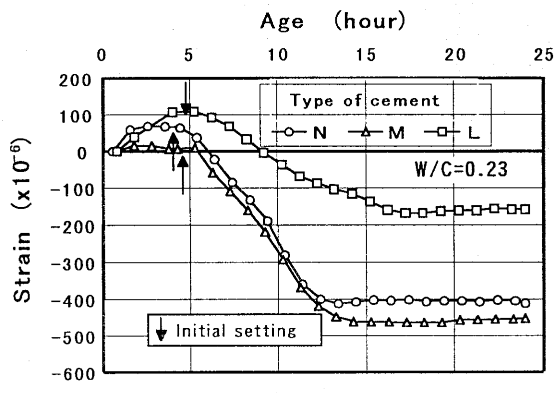

Fig.2 Length Change of Concrete after Casting

4.2 Test method for autogenous shrinkage

The change in length of concrete with a water-cement ratio of 0.23 is shown in Fig.2. The measurements are done with eddy-current displacement sensors and have been started immediately after casting. Thermal expansion due to cement hydration has been subtracted under the assumption that the coefficient of thermal expansion of concrete was 10×10^{-6}/℃. It can be seen from this figure that shrinkage initiates at the time of initial setting. Clearly, shrinkage should be measured from the initial setting time for concrete with a low water-cement ratio.

In this study, autogenous shrinkage was measured according to the "Test method for autogenous shrinkage and autogenous expansion of cement paste, mortar and concrete" as proposed by the Japan Concrete Institute (JCI)[17]. The tests were conducted with 100×100×400 mm concrete specimens at 20℃ under sealed conditions from the initial setting time to the age of 3 months. The maximum change in mass of tested specimen was no more than 0.02% during the test periods (it is specified as 0.05% or less in the JCI method), so the influence of moisture movement to or from the specimens can be ignored.

5. PROPOSED MODEL FOR AUTOGENOUS SHRINKAGE OF CONCRETE

Equation (4) is the proposed prediction model, where autogenous shrinkage is expressed as the product of the ultimate value and the development with time. In order to take into account the effect of cement type, a coefficient γ is introduced. The ultimate value $\varepsilon_{c0}(w/b)$ and its development with time $\beta(t)$ are obtained by approximation from observed values.

$$\varepsilon_c(t) = \gamma\ \varepsilon_{c0}(w/b)\ \beta(t) \times 10^{-6} \tag{4}$$

For $0.2 \leqq w/b \leqq 0.5$:

$$\varepsilon_{c0}(w/b) = 3070\exp\{-7.2(w/b)\} \tag{5}$$

For $0.5 < w/b$:

$$\varepsilon_{c0}(w/b) = 80 \tag{6}$$

$$\beta(t) = [1-\exp\{-a(t-t_0)^b\}] \tag{7}$$

where,
$\varepsilon_c(t)$ is autogenous shrinkage of concrete at age t
γ is a coefficient describing the effect of cement type (γ =1.0 for ordinary Portland cement)

$\varepsilon_{c0}(w/b)$ is the ultimate autogenous shrinkage
$\beta(t)$ is a coefficient describing the development of autogenous shrinkage over time
w/b is the water-binder ratio
a and **b** are constants
t is age in days
t_0 is initial setting time in days

If the concrete temperature is not 20℃, t and t_0 are modified using eq. (8)

Table 3 Coefficients **a** and **b** in eq.(6)

w/c	a	b
0.20	1.2	0.4
0.23	1.5	0.4
0.30	0.6	0.5
0.40	0.1	0.7
more than 0.50	0.03	0.8

$$t, t_0 = \sum_{i=1}^{n} \Delta t_i \cdot \exp\left[13.65 - \frac{4000}{273 + T(\Delta t_i)/T_0}\right] \quad (8)$$

where,
Δt_i is the number of days on which a temperature T (℃) prevails
$T(\Delta t_i)$ is the temperature over time period Δt_i
T_0=1℃

The prediction model for autogenous shrinkage (eq. (4)) is valid for concretes with water-cement ratios ranging from 0.20 to 0.56, and with a normal volume concentration of aggregate, at ambient temperatures ranging from 20℃ to 60℃.

5.1 Influence of water-binder ratio

The water-binder ratio (w/b) is taken as the main variable in the function expressing the ultimate value of autogenous shrinkage $\varepsilon_{c0}(w/b)$, although ε_{c0} is independent of w/b for concrete with a w/b of more than 0.50. In Fig.3, the calculated values are compared with observed ones for concrete at the age of 91 days. Since most autogenous shrinkage has already occurred by this age, it can be seen from this figure that the ultimate value of autogenous shrinkage is properly predicted by the proposed equation.

Autogenous shrinkage develops faster at an early age, and reaches its ultimate value at an earlier ages, as the water-cement ratio is reduced. Therefore, the coefficients **a** and **b** in eq. (7) are dependent upon water-cement ratio. Values of **a** and **b** obtained from observations are shown in Table 3. Figure 4 shows the relationship between observed $\varepsilon_c(t)/\varepsilon_{c0}$ and the value calculated using eq. (7). The calculated values are in good agreement with the observed ones.

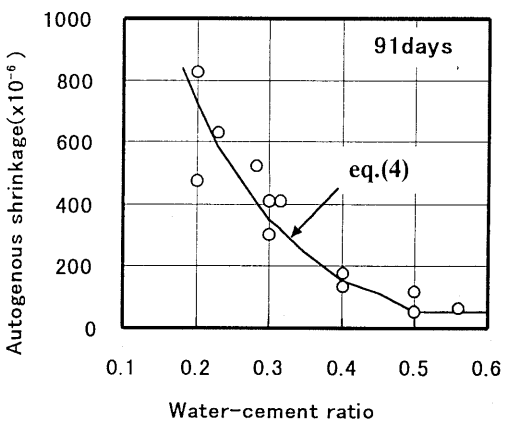

Fig.3 Relation between w/c and Autogenous Shrinkage

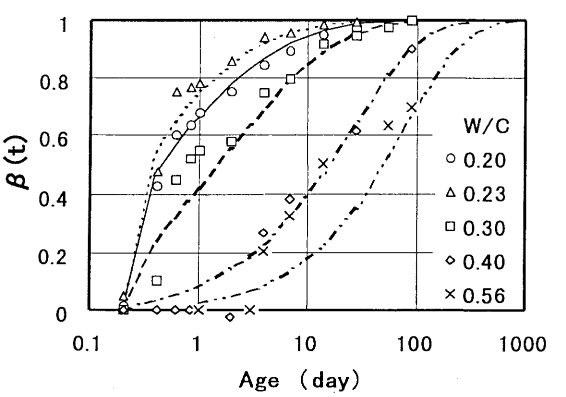

Fig.4 Relation between Age and $\beta(t)$

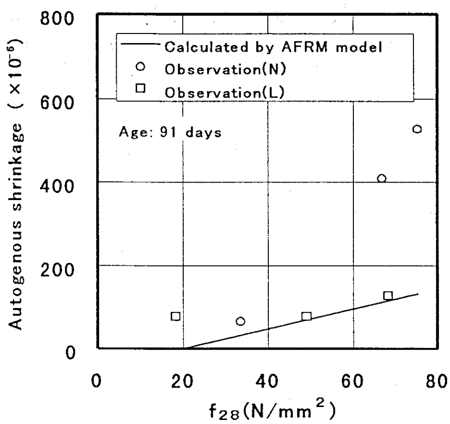

Fig.5 Autogenous Shrinkage vs. Compressive Strength

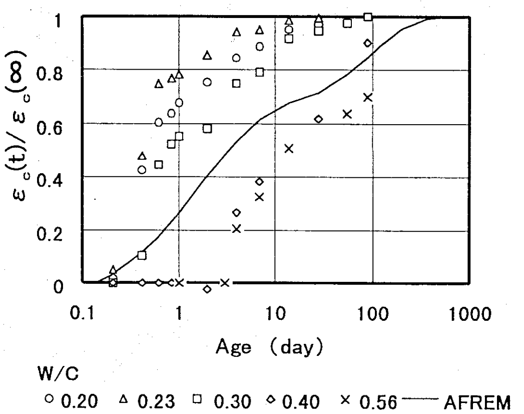

Fig.6 Development of Autogenous Shrinkage

Observed autogenous shrinkage is also compared with values calculated by using the AFRM model(eqs.(1), (2), and (3)). Since this model is a function of compressive strength of concrete, both observed and calculated values are shown in Fig.5 in relation to compressive strength. For concrete with ordinary Portland cement, the AFRM model gives an underestimate. If the development of compressive strength is estimated by AFRM model, the influence of w/b on the rate of autogenous shrinkage is not indicated, as shown in Fig.6. Therefore, it can be said that compressive strength is not a suitable factor for the prediction model, and that the influence cement type and water-cement ratio needs to be taken into account.

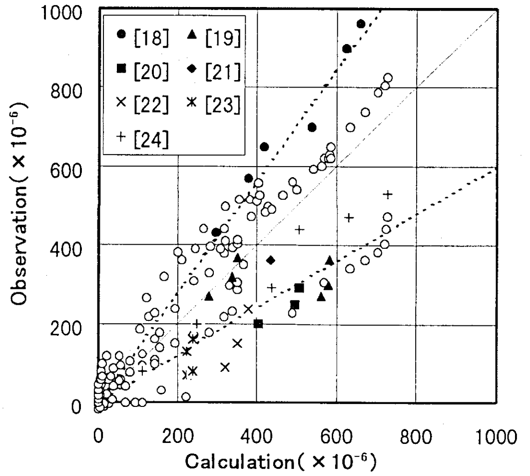

Fig.7 Relation between Observed and Calculated Autogenous Shrinkage (Ordinary Portland Cement, w/c=0.20-0.56)

The relationship between observed and calculated autogenous shrinkage for 28 different concretes made with ordinary Portland cement, where the water-cement ratio ranges from 0.2 to 0.56, is shown in Fig.7. Data for fifteen of the concretes in this figure are from the literatures[18]-[24]. In some of these references strain measurements were carried out with embedded strain gauges, while dial gauges and contact gauges were used in this study. When the observed setting time was not available in the literatures, t_0 was taken to be 0.2. It can be seen from this figure that autogenous shrinkage of concrete can be estimated using the proposed model with an error of no greater than 40%.

5.2 Influence of concrete temperature

As noted in chapter 3.5, autogenous shrinkage of concrete occurs more rapidly at an early age at high temperature than at normal temperature. In the proposed model, the effect of temperature is taken into account by adjusting the concrete age to an effective age according to eq. (8). Experimental results for concrete at different temperature are shown in Fig. 8 and Fig. 9 along with the calculated values[4]. In the experiment, concrete temperature rose immediately after casting in a temperature controlled chamber, and autogenous shrinkage was obtained after the concrete temperature reached a specified constant level. Since the constant γ for these mixtures is not available, it is assumed that $\gamma=1.3$ and $t_0=1.0$ for Fig.8, and $\gamma=1.0$ and $t_0=0.8$ for Fig.9. From these experimental results, it may be deduced that autogenous shrinkage of concrete at various temperatures can be estimated using the proposed model.

5.3 Influence of cement and mineral admixtures

As previously mentioned, coefficients **a** and **b** in eq. (7) have been determined for each w/b, and they do not vary with the type of cement. The influence of cement type is estimated only by using coefficient γ. Calculated and observed autogenous shrinkage strain at the age of 91 days is shown in Fig. 10 and Fig. 11, and autogenous shrinkage over time is shown in Fig. 12 and Fig.13, where moderate heat Portland cement (M) and belite-rich cement (L) (C_2S: 53.3-57.8 %) are used respectively. Although a precise determination of γ is difficult because of a lack of data, it is about 0.7 for cement M and about 0.6 for cement L. It can be seen that the autogenous shrinkage of concrete made with different types of cement can be calculated using the proposed equation.

The influence of blast furnace slag on autogenous shrinkage is also estimated using γ. From experimental data obtained in a previous research[11], where 50% of ordinary Portland cement was

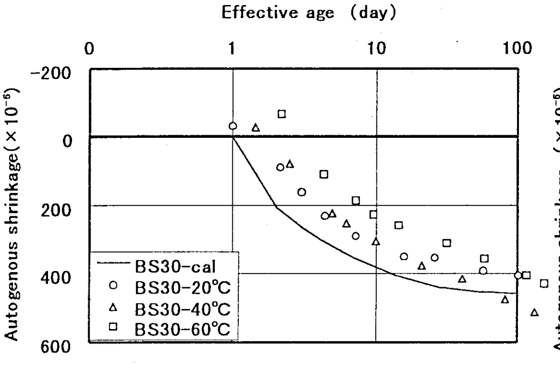

Fig.8 Effective Age vs. Autogenous Shrinkage (70% of cement is replaced by blast furnace slag with 8000 Blaine, w/b=0.30)

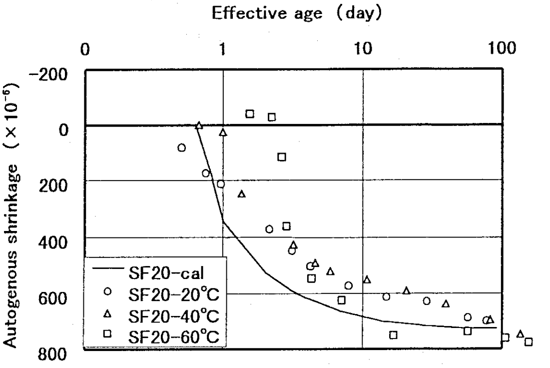

Fig.9 Effective Age vs. Autogenous Shrinkage (10% of cement is replaced by silica fume, w/b=0.20)

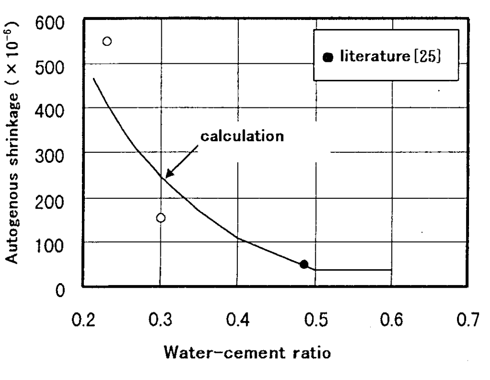

Fig.10 Relation between w/c and Autogenous Shrinkage (Moderate heat cement, 91 days)

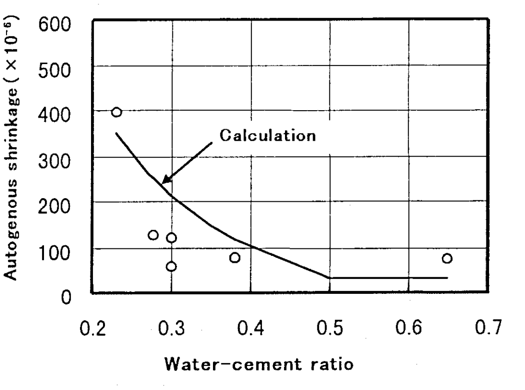

Fig.11 Relation between w/c and Autogenous Shrinkage (Belite-rich Cement, 91 days)

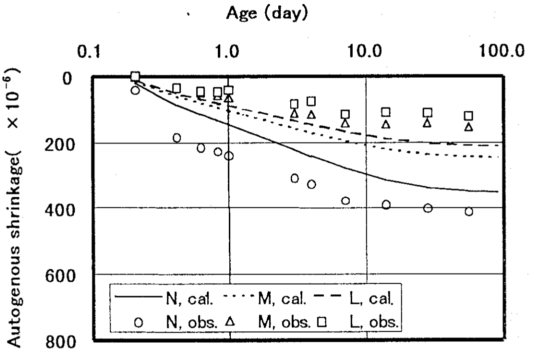

Fig.12 Relation between Age and Autogenous Shrinkage (w/c=0.30)

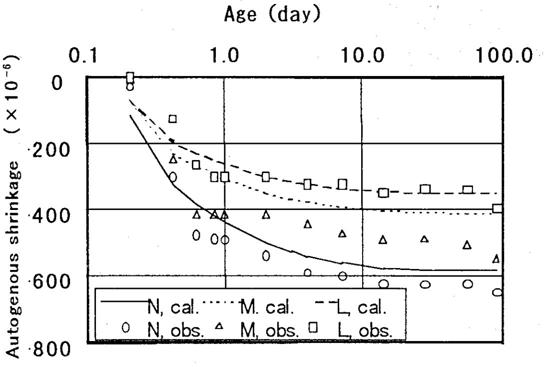

Fig.13 Relation between Age and Autogenous Shrinkage (w/c=0.23)

replaced by blast furnace slag, γ is about 0.9, 1.0, and 1.3 for blast furnace slag with 4000 cm^2/g blaine and w/b=0.2, 0.3, and 0.4, respectively, and γ is about 1.2, 1.3 and 1.6, respectively, for 6000 cm^2/g.

6. CONCLUSIONS

A prediction model for the autogenous shrinkage of concrete has been proposed for practical uses, and its accuracy has been examined using previously reported data. The proposed model is applicable to ordinary Portland cement concretes with a normal volume concentration of aggregate and with w/c ranging form 0.2 to 0.56. The influence of concrete temperature can be estimated using an effective age in place of age in the model. The influence of the type of cement and mineral admixtures can be estimated using coefficient γ, although the exact value of γ for each material admixture must be determined from a number of experimental results.

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