PREDICTION OF CREEP AND SHRINKAGE OF CONCRETE

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ABSTRACT

The author proposed new prediction equations for creep and shrinkage of concrete by a statistical method on the basis of many experimental data by the author. The accuracy of the new equations was verified by many experimental data by the author and in references. The new equations can estimate concrete creep and shrinkage strains with a certain degree of accuracy. These new prediction equations of creep and shrinkage of concrete were adopted as Japanese standard methods by Japan Society of Civil Engineers (JSCE) in the revised Standard Specification for Design and Construction of Concrete Structure published in 1996. In this paper, new prediction equations for creep and shrinkage of concrete are presented. The comparison between the proposed new equations and CEB/FIP-90 Model and other models is discussed. I also discussed the effect of ambient temperature on the creep and shrinkage of concrete. It was clarified that the magnitude of creep and shrinkage was highly influenced by the difference of the season in which concrete was cast, and also influenced by the temperature of curing water before application of load.

KEYWORDS

Creep; Shrinkage; Strain; Prediction Equation; Temperature History; Casting Season.

INTRODUCTION

New prediction equations for creep and shrinkage of concrete were proposed. These equations were derived by a statistical method based on many experimental data. The accuracy of the new equations are verified by many experimental data by the author and in references.

In "Standard Specification for Design and Construction of Concrete Structure - 1991" published by Japan Society of Civil Engineers (JSCE) [JSCE. (1991)], we find the following statements concerning the estimation of creep and shrinkage in the design of concrete structure. In the examination of ultimate limit states for deformation, creep shall be taken into account. In the examination of serviceability limit states, long-term displacement and deformation of structures or members shall be computed by taking into account the effects of drying shrinkage and creep. Time dependent loss of prestressing force in prestressed concrete members shall be computed considering the effects of shrinkage and creep. It is also described that creep and shrinkage strains can be predicted by CEB/FIP - 78 equations [CEB. (1978)]. JSCE was revised Standard Specification for Design and Construction of Concrete Structure in 1996. Our model for prediction of creep and shrinkage was adopted by JSCE as Japanese standard equations in the revised Standard Specification for Design and Construction of Concrete Structures published in 1996.

In our model, the effect of temperature on creep and shrinkage of concrete is not taken into account. In countries like Japan which have four seasons with significant variation in temperature, it is very important to predict the effect of ambient temperature on creep and shrinkage of concrete effectively and appropriately for design of concrete structures. In this study, we carried out the creep and shrinkage test under constant and varying histories of temperature. The creep and shrinkage tests corresponding to actual circumstance were also carried out in the room where the effect of rain and wind were negligible. We discussed the relationship between the creep and shrinkage obtained in constant temperature and constant relative humidity room and those observed under the actual conditions. The effect of temperature when concrete was cast was also studied. CEB-FIP/90 Model [CEB. (1991)] takes the effect of temperature of curing water before application of load into account to predict creep. We also studied the effect of temperature of curing water on creep and shrinkage. In addition, this paper proposed a coefficient which estimated the effect of temperature history on shrinkage.

EXPERIMENTS

The outline of the experiment which was done for the establishment of the proportion of concrete prediction equations and the discussion of the application of these equations is as follows. An ordinary portland cement (type-I) was used. Fine aggregate is river sand (specific gravity: 2.61, water absorption: 1.61%, F.M.: 2.51), and coarse aggregate is crushed stone (maximum size: 20 mm, specific gravity: 2.75, water absorption: 0.74%, F.M.: 6.47). The mix proportions of concretes used in the shrinkage tests are shown in Table 1. In the creep tests, concretes except for N-220/360 and N-200/360 were used. The ages when drying starts and the loading ages were 3, 7, 14, 28 and 56 days. Ambient relative humidity were 60 and 80%RH. In the shrinkage tests, 160 different beam specimens of 10x10x40 cm, 15x15x53 cm and 30x30x120 cm were used. In the creep tests, 104

Table 1 Mix proportion of concrete

Specimen	W/C %	W kg/m³	C kg/m³	S kg/m³	G kg/m³	S/a %	Specimen	W/C %	W kg/m³	C kg/m³	S kg/m³	G kg/m³	S/a %
K-200/420	47.6	200	420	677	1009	41.4	I-180/400	45.0	180	400	764	1006	44.0
K-195/420	46.4	195	420	689	1009	41.8	I-160/400	40,0	160	400	787	1036	44,0
K-190/420	45.2	190	420	702	1009	42.2	I-180/380	47.4	180	380	771	1016	44.0
K-185/420	44.0	185	420	714	1009	42.7	I-220/360	61.1	220	360	733	965	44.0
K-180/420	42.9	180	420	727	1009	43.1	I-190/360	52.8	190	360	767	1010	44.0
K-180/360	50.0	180	360	774	1009	44.6	I-180/360	50.0	180	360	778	1025	44.0
K-175/360	48.6	175	360	786	1009	45.0	I-180/340	52.9	180	340	786	1035	44.0
K-185/320	57.8	185	320	756	1048	43.0	I-200/320	62.5	200	320	770	1014	44.0
K-180/320	56.3	180	320	762	1055	43.0	I-160/320	50.0	160	320	816	1074	44.0
K-175/320	54.7	175	320	767	1063	43.0	I-190/280	67.9	190	280	796	1048	44,0
K-170/320	53.1	170	320	773	1070	43.0	I-160/280	57.1	160	280	830	1093	44,0
K-165/320	51.6	165	320	778	1078	43.0	I-170/260	65.4	170	260	826	1088	44,0
K-175/280	62.5	175	280	799	1064	44.0	I-160/260	61.5	160	260	837	1103	44.0
K-170/280	60.7	170	280	805	1072	44,0	I-130/260	50.0	130	260	871	1148	44.0
H-180/420	42.9	180	420	757	1012	44.0	0-210/420	50.0	210	420	720	973	44,0
H-200/360	55.6	200	360	756	1010	44.0	0-220/360	61.1	220	360	730	987	44.0
H-180/360	50.0	180	360	779	1041	44,0	0-180/360	50.0	180	360	775	1048	44.0
H-160/360	44.4	160	360	801	1071	44.0	0-162/360	45.0	162	360	796	1076	44.0
H-180/320	56.3	180	320	792	1059	44.0	0-160/320	50.0	160	320	812	1098	44.0
H-180/280	64.3	180	280	807	1079	44.0	0-160/260	61.5	160	260	834	1127	44.0
I-220/500	44.0	220	500	683	899	44.0	0-143/260	55.0	143	260	853	1153	44.0
I-200/500	40.0	200	500	705	929	44.0	0-130/260	50.0	130	260	868	1173	44.0
I-230/460	50.0	230	460	686	903	44.0	N-180/360	50.0	180	360	784	1044	44.0
I-180/460	39.1	180	460	742	978	44.0	N-160/320	50.0	160	320	822	1094	44.0
I-180/435	41.4	180	435	751	990	44.0	N-140/280	50.0	140	280	859	1144	44.0
I-210/420	50.0	210	420	723	952	44.0	N-220/360	61.1	220	360	739	984	44,0
I-160/420	38.1	160	420	780	1027	44.0	N-200/360	55.6	200	360	762	1014	44,0

different beam specimens of 10x10x38 cm, 15x15x51 cm were used. Fig.1 shows the frequency distribution of the compressive strength of the concrete in Table 1 at the age when drying starts. In order to change the value of V/S, some surfaces of some specimens were sealed with paraffin. Strain was measured by Whittmore strain meter whose minimum reading is 1/1000 mm. The period of measurement was about 150~200 days.

The outline of the experiments which were carried out on the effect of ambient temperature on creep and shrinkage of concrete is as follows. Mixture proportion of concrete is shown in Table 2. The strength of concrete at the age of 28 days is 36.9 MPa. The slump is 5.1 cm. The air content is 2.1%. The size of the prism specimen for measuring creep and shrinkage strain is 100x100x400 mm. The surfaces of the specimen are not sealed. The age at the start of drying is 14 days. The first application of load for creep test specimen is also 14 days. The first application of load for creep test specimen is also 14 days. The other experimental conditions are the same as the experiment which was done for the establishment of the proportion of concrete prediction equations and the discussion of the application of these equations.

The creep and shrinkage test corresponding to actual environmental conditions were carried out in a room where the effects of rain and wind were negligible. The following temperature and relative humidity feature in the room is described from records that were kept for two years. The change of temperature in a day is very small, but, over a year is very big and ranged from 5℃ to 35℃. The concrete specimens which were tested under actual conditions were cast in March (temperature: 14℃), July (temperature: 29℃), September (temperature: 25℃) and December (temperature: 8℃). Table 3 shows the temperature histories applied to the specimens in the constant temperature and constant humidity room. The period for one interval of temperature history is 70 days. The relative humidity is 75±5%. The coefficient of thermal expansion used to isolate the shrinkage strain from experimental data is 9.6x10-6. This value was experimentally obtained by using the concrete specimen whose size and mix proportion are the same as the shrinkage test specimen.

Table 2 Mix proportion of concrete

Gmax (mm)	Slump (cm)	Air (%)	W/C (%)	s/a (%)	Unit weight (kg/m^3)				
					W	C	S	G	Admix.
20	5.1±3.3	2.1±0.1	60	44.6	200	333	785	1027	–

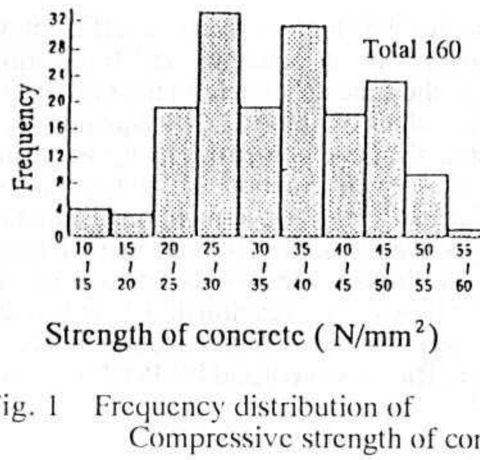

Fig. 1 Frequency distribution of Compressive strength of concrete

Table 3 Temperature histories

1st period (70days)	2nd period (70days)	3rd period (70days)	4th period (70days)
5±0.5℃	20±1.0℃	35±1.0℃	20±1.0℃
20±1.0℃	35±1.0℃	20±1.0℃	5±0.5℃
35±1.0℃	20±1.0℃	5±0.5℃	20±1.0℃
20±1.0℃	5±0.5℃	20±1.0℃	35±1.0℃
	5±0.5℃		
5±0.5℃	20±1.0℃		
	35±1.0℃		
	5±0.5℃		
20±1.0℃	20±1.0℃	35±1.0℃	
	35±1.0℃		
	5±0.5℃		
35±1.0℃	20±1.0℃		
	35±1.0℃		

PROPOSITION OF PREDICTION EQUATIONS FOR CREEP AND SHRINKAGE

Prediction equations of creep and shrinkage are proposed as follows. These prediction equations were derived by a statistical method on the basis of many experimental data by the author. Creep is given by the following equations.

$$\varepsilon'_{cc}(t, t', t_0) = \varepsilon'_{cr\infty} \cdot [1 - \exp\{-0.09(t - t')^{0.6}\}] \quad (1)$$

$$\varepsilon'_{cr\infty} = \varepsilon'_{bc\infty} + \varepsilon'_{dc\infty} \quad (2)$$

where, $\varepsilon'_{cc}(t, t', t_0)$ is predicted specific creep (x 10^{-10} /(N/mm^2)), $\varepsilon'_{bc\infty}$ is basic creep (x 10^{-10}/(N/mm^2)), $\varepsilon'_{dc\infty}$ is drying creep (x 10^{-10} /(N/mm^2)), t is the age of the concrete (days), t' is the age of the concrete at loading (days), t_0 is the age of the concrete at the beginning of drying (days).

In this model, basic creep may be calculated as follows taking into account those parameters, i.e. W/C, C+W, and t'. The multiple correlation coefficient of this model is 0.82.

$$\varepsilon'_{bc\infty} = 15\,(C+W)^2(W/C)^{2.4}(\ln t')^{-0.67} \quad (3)$$

where, C is cement content (kg/m^3), W is water content (kg/m^3).

Considering those parameters, i.e. W/C, C+W, V/S, RH and t_0, drying creep is given as follows. The multiple correlation coefficient of this model is 0.80.

$$\varepsilon'_{dc\infty} = 4500\,(W/C)^{4.2}(C+W)^{1.4}[\ln\{(V/S)/10\}]^{-2.2}(1-RH/100)^{0.36}(t_0)^{-0.3} \quad (4)$$

where, V/S is volume - surface ratio of concrete member (mm), and RH is ambient relative humidity (%).

Shrinkage is predicted by the following equations.

$$\varepsilon'_{cs}(t, t_0) = \varepsilon'_{sh} \cdot [1 - \exp\{-0.108(t-t_0)^{0.56}\}] \quad (5)$$

$$\varepsilon'_{sh} = -50 + 78\{1 - \exp(RH/100)\} + 38 \ln W - 5[\ln\{(V/S)/10\}]^2 \quad (6)$$

where, $\varepsilon'_{cs}(t, t_0)$ is predicted shrinkage ($\times 10^{-5}$), and ε'_{sh} is ultimate shrinkage ($\times 10^{-5}$). The multiple correlation coefficient of this model is 0.90.

VERIFICATION OF PREDICTION EQUATION

Figs. 2~4 show the relationships between the predicted values of creep coefficient by ACI-209 equation [ACI. (1982)], CEB/FIP-90 equation and our equation (JSCE equation) and our experimental data, respectively. In the figures, the time dependent behaviors of 104 kinds of specimens are shown. In Fig. 2, the predicted values by the ACI-209 equation are a little lower than the experimental ones. In this equation, the development of creep with time is expressed by the hyperbolic function . Creep after a given duration of loading can be predicted from the product of an ultimate creep coefficient and the above-mentioned function of time development. The ultimate creep coefficient is also given by the product of many factors which have an influence on creep behavior. The linear independence of each one of the influencing factors must be investigated. Fig. 3 shows the relationship between the predicted value by CEB/FIP-90 equation and our experiment data. This equation is also a product type model. As a matter of course, the creep coefficients predicted by JSCE equation agree with the experimental values as shown in Fig. 4.

In order to confirm the accuracy of the proposed prediction equation of creep , the experimental data other than the authors' should be used. Fig. 5 shows the relationship between the predicted creep coefficient by CEB/FIP-90 equation and the data which were used when the CEB/FIP-90 equation was derived. In Fig. 6, the adequacy of the proposed equation is investigated by the CEB data used in Fig.5. The predicted creep coefficients by JSCE equation agree with the CEB/FIP experimental data very well.

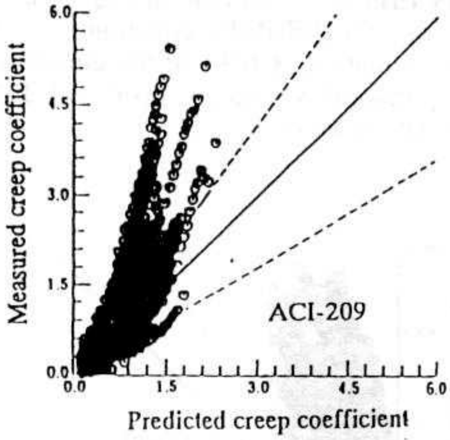

Fig. 2 Comparison between measured and predicted creep

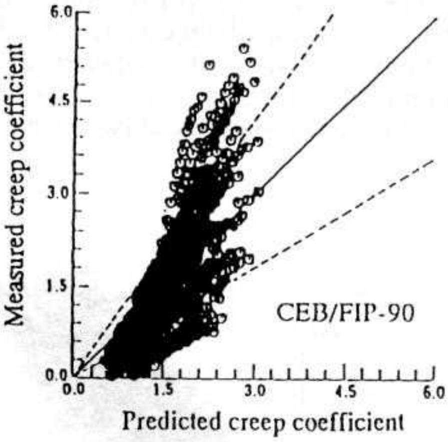

Fig. 3 Comparison between measured and predicted creep

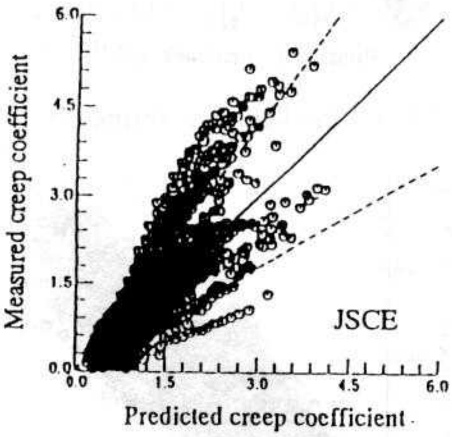

Fig. 4 Comparison between measured and predicted creep

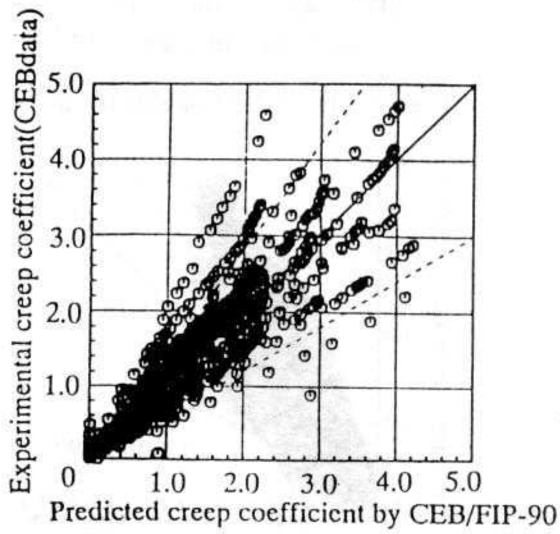

Fig. 5 Comparison between measured and predicted creep

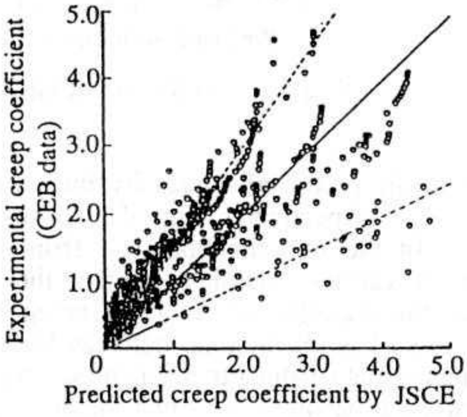

Fig. 6 Comparison between measured and predicted creep

Figs. 7 ~ 10 show the relationship between the predicted values of shrinkage by ACI-209 equation, CEB/FIP-78 equation, CEB/FIP-90 equation and JSCE equation and our experimental data. In the figures, the time dependent shrinkage behaviors of 160 kinds of specimens are shown. In Fig.7, the predicted values by the ACI-209 equation agree with the experimental ones. This is satisfactory for estimating shrinkage in ordinary plain concrete. The predicted values by the CEB/FIP-78 equation are much lower than the experimental ones as shown in Fig.8. This is because the base values of shrinkage are small. Because of this tendency, CEB/FIP proposed a new equation (CEB/FIP-90 equation). Fig. 9 shows the relationship between the predicted values by the CEB/FIP-90 equation and the experimental ones. In comparison with CEB/FIP-78 equation, CEB/FIP-90 equation is improved in the accuracy of predicted values. The predicted values by proposed JSCE equation agree with the experimental data, because our data is used.

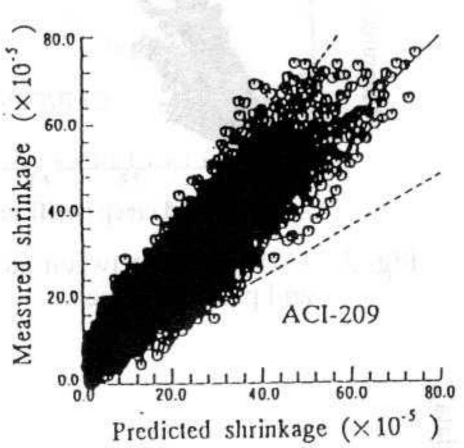

Fig. 7 Prediction of shrinkage

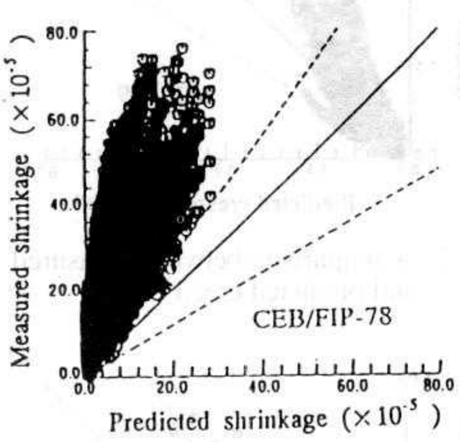

Fig.8 Prediction of shrinkage

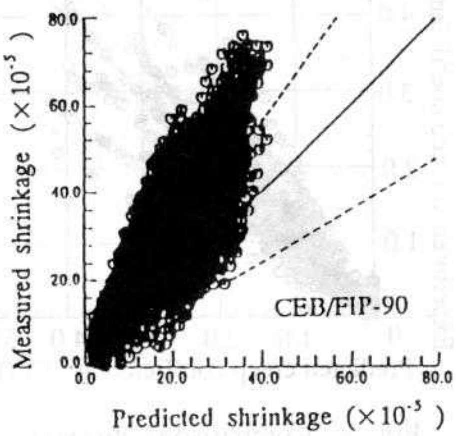

Fig. 9 Prediction of shrinkage

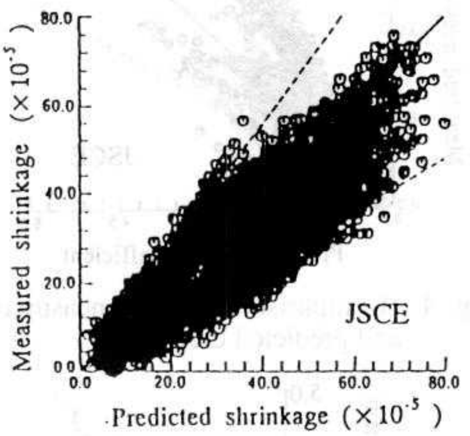

Fig.10 Prediction of shrinkage

Fig. 11 and 12 show the relationships between the predicted values by the CEB/FIP-90 equation and JSCE equation and CEB/FIP data, respectively. Fig. 12 shows that the predicted values by proposed JSCE equation fit the experimental data from the other organization very closely. Figs. 13 and 14 show the further example to confirm the efficiency and applicability of JSCE equations. Fig. 13 clarifies the efficiency of JSCE creep prediction equation by Wagner's data [Wagner. (1958)]. Fig. 14 is relationship between the calculated shrinkage by JSCE equation and the experimental data from other Japanese organization [Iioka and Toyohuku. (1976)]. From these figures, it becomes clear that the predicted creep and shrinkage by JSCE equations agree with the experimental data very well.

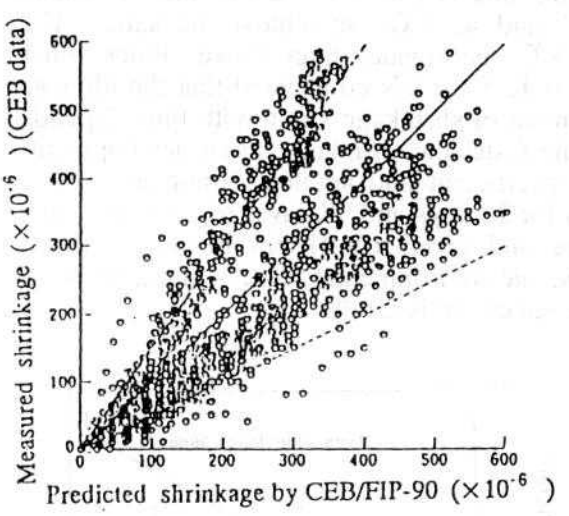

Fig. 11 Comparison between measured and predicted shrinkage

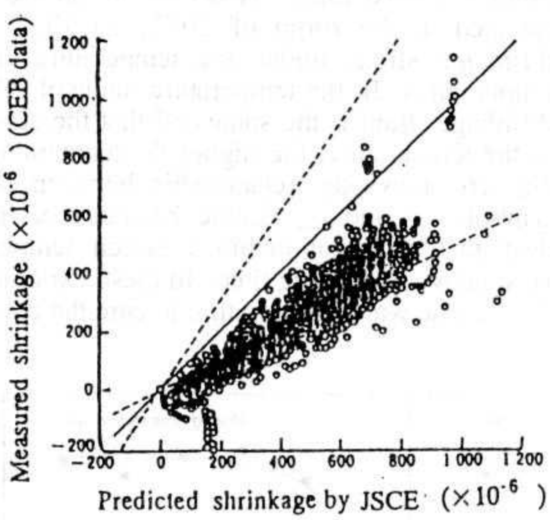

Fig.12 Comparison between measured and predicted shrinkage

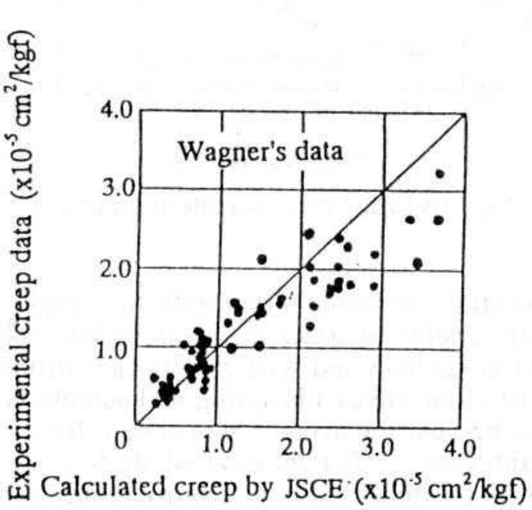

Fig.13 Comparison between measured and predicted creep

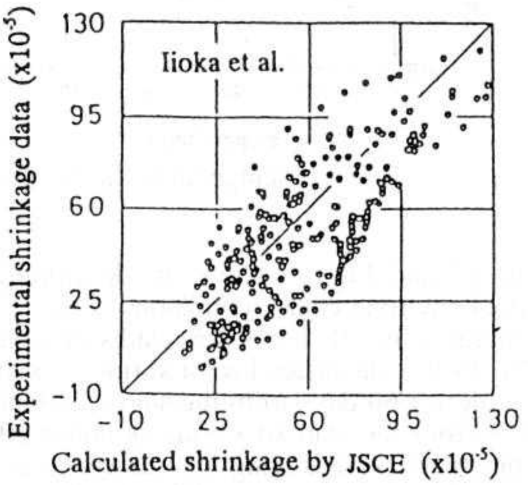

Fig.14 Comparison between measured and predicted shrinkage

THE EFFECT OF TEMPERATURE

In Standard Specification for Design and Construction of Concrete Structures, the effect of an elevated temperature T to which concrete is exposed prior to or during loading is taken into account by eq. (7) proposed in CEB/FIP-90 equation.

$$t,\ t',\ t_0 = \sum_{i=1}^{n} \Delta t_i \cdot \exp\left[13.65 - \frac{4000}{273 + T(\Delta t_i)/T_0}\right] \qquad (7)$$

where $T(\Delta t_i)$ is in (℃) during the time period Δt_i, Δt_i is number of days where the temperature T prevails, T_0 is 1 ℃.

Fig. 15 shows the relationship between shrinkage strain and ambient temperature. The symbols ○ and ● denote the shrinkage strain for 28 days and 140 days, respectively. When the drying time is 28 days, the relationship between temperature and shrinkage strain is almost linear. However, when the drying time is 140 days, the shrinkage strains obtained in the room of 20℃, 27.5℃, 35℃ and 42.5℃ are almost the same. The shrinkage strain under the temperature of 5℃ is smaller than those under other temperatures. In the temperature range of 20℃ to 42.5℃, it is considered that the ultimate shrinkage strain is the same and that the development of shrinkage strain with time depends on the temperature; the higher the temperature, the faster the shrinkage strain development. Fig. 16 shows the relationship between creep coefficient and ambient temperature. The symbols ○ and □ denote the creep coefficient for 28 days and 98 days, respectively. It is clear that the relationship between temperature and creep coefficient is almost linear irrespective of loading time. In these experiments, the environmental relative humidity is 75 ±5%. The water temperature to cure the concrete specimen is 20 ℃.

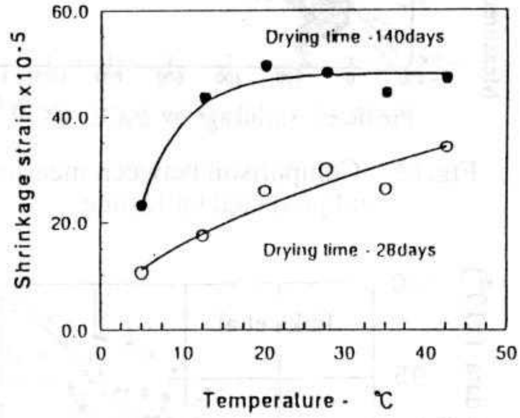

Fig. 15 Effect of temperature on shrinkage

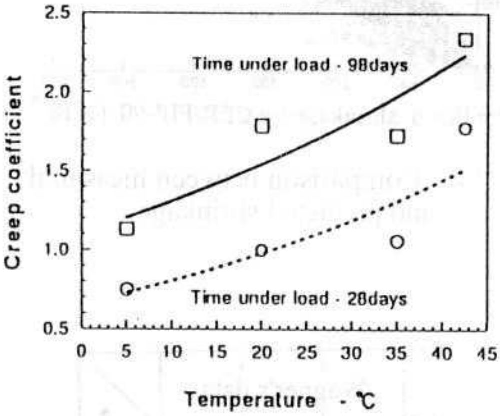

Fig. 16 Effect of temperature on creep

Fig. 17 and Fig. 18 show the development of concrete shrinkage strain with time under actual environmental conditions. Fig. 17 shows the results of concrete cast in spring and autumn. Fig. 18 shows the results of concrete cast in summer and winter. It is clear from Fig. 17 that the difference of shrinkage strain between concrete cast in spring and autumn is not big for 60 days from the start of drying. That is because the average temperature for 60 days from the start of drying is about 20℃ in both cases. After 60 days of drying, the temperature surrounding the concrete cast in spring is higher than that surrounding the concrete cast in autumn and the shrinkage strain of concrete cast in spring is bigger than that of the concrete cast in autumn. After one year of drying, however, the shrinkage strain of concrete cast in spring is almost the same as that of concrete cast in autumn. On the other hand, it is clear from Fig. 18 that the shrinkage strain of concrete cast in winter is much bigger than that of concrete cast in the summer.

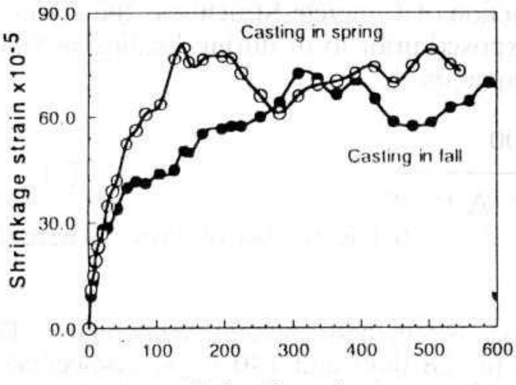

Fig. 17 Shrinkage under actual environment

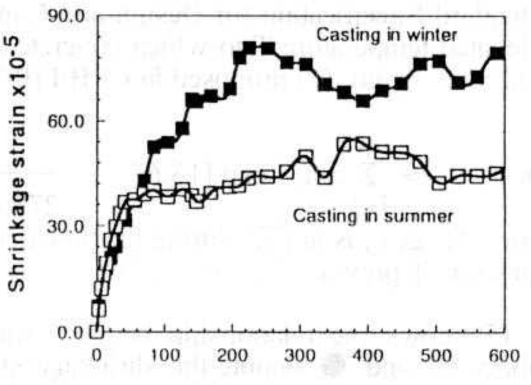

Fig. 18 Shrinkage under actual environment

Fig. 19 and Fig. 20 show the development of concrete creep coefficient with time under actual environmental conditions. It is clear from Fig. 19 that the difference of creep coefficient between concrete cast in spring and autumn is not big. On the other hand, the creep coefficient of concrete cast in winter is much bigger than that of concrete cast in the summer as shown in Fig. 20. These data were obtained by using concrete specimen stored in the room where the ambient temperature and the relative humidity were not controlled. It means that the concrete was suffered variable temperature in curing and variable temperature and relative humidity in drying. It is evident that the creep and shrinkage strain are influenced by the season in which concrete is cast.

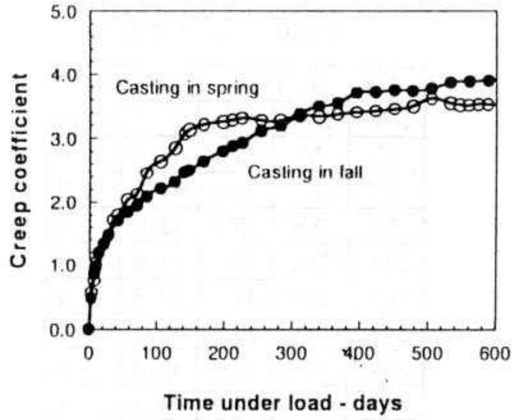

Fig.19 Creep under actual environment

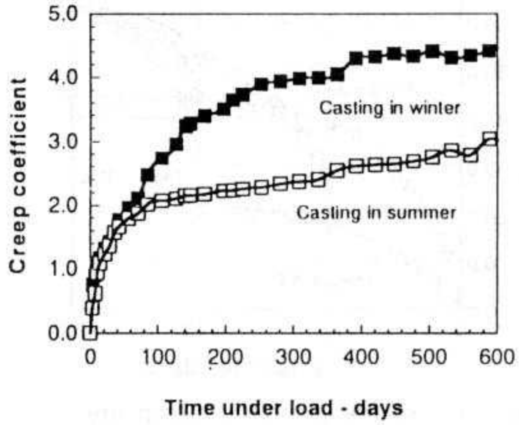

Fig. 20 Creep under actual environment

Fig. 21 and Fig. 22 show the development of concrete shrinkage strain with time subjected to the temperature histories of 20℃→35℃→20℃→5℃, 20℃→5℃→20℃→35℃, 5℃→20℃→35℃→20℃ and 35℃→20℃→5℃→20℃ in the constant relative humidity room. Each period of temperature history is 70 days. The temperature history 20℃→35℃→20℃→5℃, 35℃→20℃→5℃→20℃, 20℃→5℃→20℃→35℃ and 5℃→20℃→35℃→20℃ are simulated for the concrete cast in spring, summer, autumn and winter, respectively. The tendency of shrinkage strain development with time and the magnitude of shrinkage strain for one year of drying given in Fig. 21 and in Fig. 22 are very similar to those shown in Fig. 17 and Fig. 18, respectively. This means that the effect of change of relative humidity on concrete shrinkage strain is very small and that the shrinkage strain under actual conditions can be simulated in the constant relative humidity room. The shrinkage strain of concrete with increasing temperature history is much bigger than that in other temperature history.

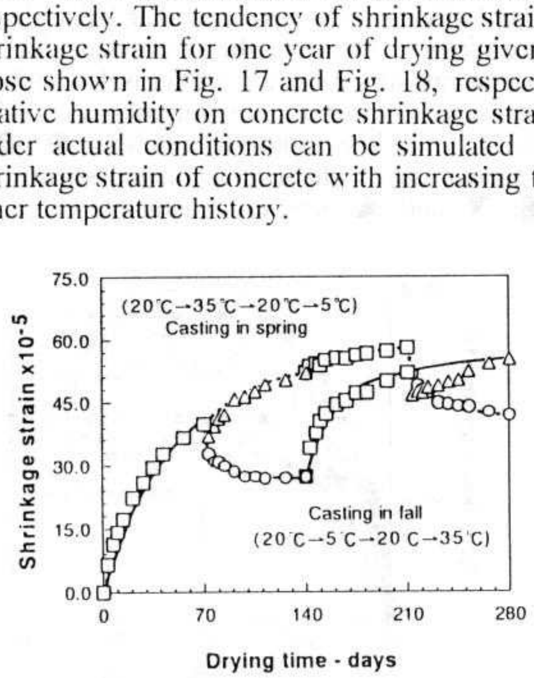

Fig. 21 Effect of temperature history on shrinkage

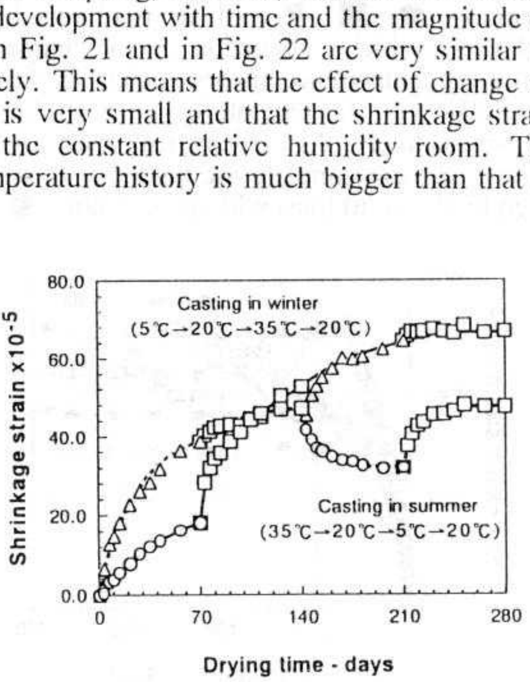

Fig. 22 Effect of temperature history on shrinkage

Fig.23 shows the development of shrinkage strain subjected to the temperature history of 5℃→ 20℃→ 35℃, 5℃→ 5℃→ 35℃ and 35℃→ 35℃→ 35℃. The symbols ○, □ and △ denote that the ambient temperatures are 5℃, 20℃ and 35℃, respectively. As evident from this figure, the shrinkage strain subjected to increasing temperature history is bigger than that of concrete under constant temperature. Table 4 shows the shrinkage strain subjected to various temperature history whose temperature in the third period is 35℃. The drying time of the shrinkage strain shown in this table is 210 days. It is clear in this table that the shrinkage strain is bigger when the temperature is low in the first or the second period.

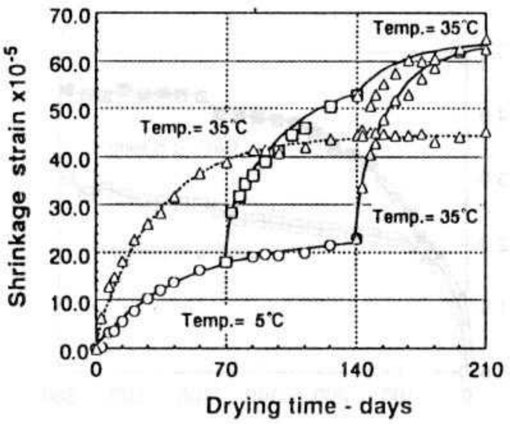

Fig. 23 Shrinkage in the increasing temperature history

Table 4 Effect of temperature history on shrinkage

Temp. history			Shrinkage	
1st	2nd	3rd	10^{-5}	Rate
5℃	35℃	35℃	65.4	1.6
5℃	20℃	35℃	64.6	1.6
5℃	5℃	35℃	62.5	1.6
20℃	35℃	35℃	54.8	1.4
20℃	20℃	35℃	53.8	1.4
35℃	20℃	35℃	46.1	1.2
35℃	5℃	35℃	45.3	1.1
20℃	5℃	35℃	44.4	1.1
35℃	35℃	35℃	39.7	1.0

Fig.24 and Fig.25 show the calculated shrinkage strain proposed by the author. The symbols ○ and □ in Fig.24 denote the shrinkage strain of concrete cast in spring and autumn, respectively. The symbols ▽ and △ in Fig.25 denote the shrinkage strain of concrete cast in winter and summer, respectively. These data are obtained by experiment. The broken lines with the symbols ●, ■, ▼ and ▲ are the shrinkage strain under constant temperature, which is equal to the average temperature from the start of drying until the drying time when the shrinkage strain is calculated. The solid lines with the symbols ●, ■, ▼ and ▲ is obtained by multiplying the above calculated data by a coefficient which depends on the temperature history. Namely, the coefficient due to increasing temperature history such as in the concrete cast in spring and winter is 1.4. While the coefficient for temperature history of the concrete cast in autumn and summer is 1.2 and 1.0, respectively. As evident from these figures, the solid lines with the symbols ●, ■, ▼ and ▲ can simulate the tendency of experimental data well. The calculated shrinkage given by the solid lines with the symbols ●, ■, ▼ and ▲ is a very reasonable value.

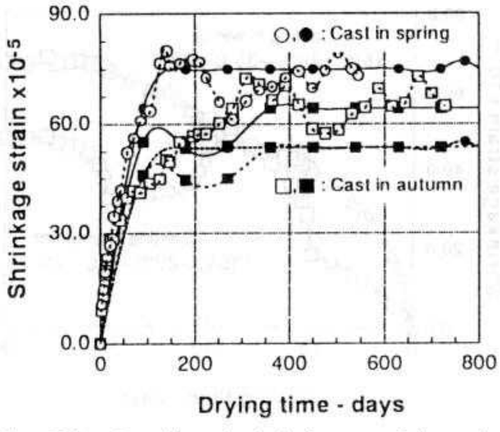

Fig. 24 Predicted shrinkage subjected to temperature history

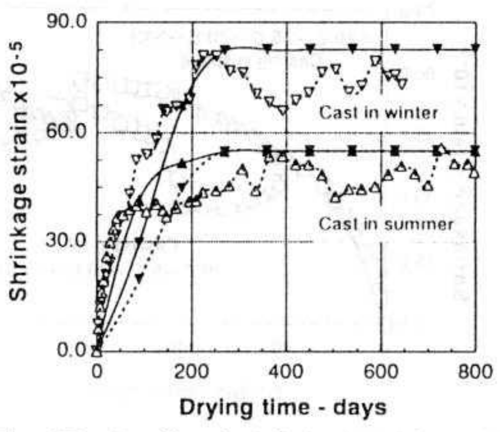

Fig. 25 Predicted shrinkage subjected to temperature history

Fig. 26 shows the development of creep coefficient with time subjected to the temperature history of 20℃→35℃→20℃→5℃ and that of 20℃→5℃→20℃→35℃ in the constant relative humidity room. Fig. 27 shows the development of creep coefficient with time subjected to the temperature history of 5℃→20℃→35℃→20℃ and that of 35℃→20℃→5℃→20℃. The development of creep coefficient with time is different depended on the temperature history. However, the magnitude of creep coefficient at 280 days after the application of load is almost the same irrespective of suffered temperature history. It is considered that the effect of temperature history in drying on ultimate creep coefficient is not so big. The magnitude of creep coefficient for one year given in Fig. 26 and in Fig. 27 are not similar to those shown in Fig. 19 and Fig. 20.

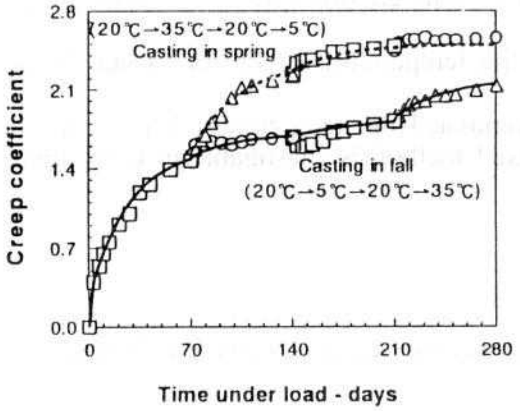

Fig. 26 Effect of temperature history on creep

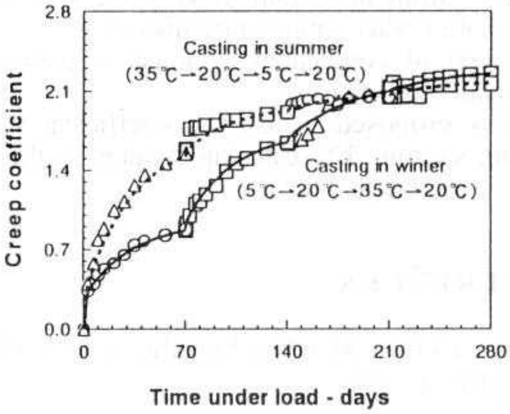

Fig. 27 Effect of temperature history on creep

Fig. 28 shows the relationship between creep coefficient and average temperature in curing. The period of application of load is 600 days. These creep coefficients are normalized with that of concrete cast in winter. The solid line is calculated data by the prediction equation of CEB-FIP/90. This prediction equation modifies the creep coefficient bigger by making the age at the start of application younger when the temperature in curing is low. There may be some discussion on the validity of the prediction equation of CEB-FIP/90. It is, however, evident that the ultimate creep coefficient of concrete is influenced by temperature in curing more than temperature history and relative humidity change in drying.

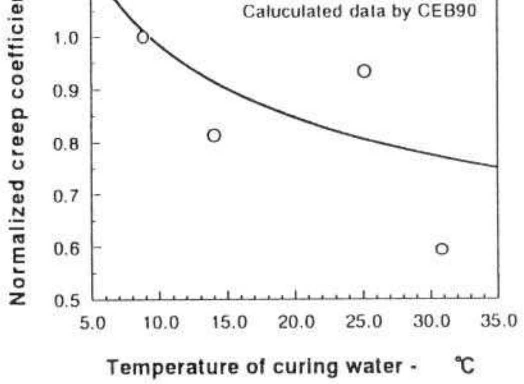

Fig. 28 Relationship between temperature of curing water and creep

CONCLUSION

The major conclusions derived from this study are as follows.

1) The new prediction equations for creep and shrinkage were proposed and the equations can estimate creep and shrinkage strains of concrete within a certain degree of accuracy.

2) In the temperature range of 20℃ to 42.5℃, it is considered that the ultimate shrinkage strain is the same and that the development of shrinkage strain with time depends on the temperature, the higher the temperature, the faster the shrinkage strain development.

3) The relationship between temperature and creep coefficient is almost linear irrespective of loading time.

4) The magnitude of creep and shrinkage is highly influenced by the difference of the season in which concrete was cast.

5) The shrinkage strain of concrete with increasing temperature history is much bigger than that in other temperature history.

6) Creep of concrete was much influenced by the temperature of curing water before application of load.

7) It is proposed to use the coefficient which simulated the temperature history of the casting season. The calculated value by the proposed method is reasonable in comparison to the experimental data.

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