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ON PREDICTING CREEP TOWARDS HIGH-STRENGTH CONCRETE

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Most of the available creep prediction models proposed by the different national building codes are valid only for concretes having compressive strengths not greater than 800kgf/cm^2 (80 MPa). A rheological viscoelastic model is proposed for predicting the creep of normal- and high-strength concretes from their basic constituents, that are cement paste and aggregate. A parametric study is carried out to compare the creep functions calculated using CEB-FIP Model Code 1990 and ACI Committee 209 with those calculated using the proposed model as well as with the available experimental data. The comparison indicated that the proposed model can predict the creep of both normal- and high-strength concretes.

Key Words *: creep properties, creep tests, high-strength concrete, viscoelastic models, creep function (creep compliance), building codes*

1. INTRODUCTION

The need to keep water/cement ratios down for durability reasons and the introduction of new admixtures and cementitious materials have allowed the production of highly workable concrete with superior mechanical properties and durability. It will not be uncommon in the near future to use concretes of high strength values of the order of 1500kgf/cm^2 (150 MPa) or more. Creep of concrete is an important phenomenon to the design engineer especially when dealing with creep-sensitive structures, such as, cantilever bridges and those with long spans or high piers, high-rise buildings, containment vessels and of course, precast and prestressed concretes. High-strength concrete is often used in particularly creep-sensitive structures. In the past, research on high-strength concrete has primarily concentrated on increasing its strength. In the last decade, however, considerable effort has been spent on studying its mechanical properties and structural behavior. Nevertheless, many aspects, such as creep, need much more detailed investigation.

Creep of concrete has, on occasion, led to serviceability problems during the life of the concrete structures. If the creep of concrete is predicted accurately and design compensations are made, the result will be better distribution of stresses in concrete structures. Unfortunately, when the deformations and deflections due to creep are excessive, or design compensations are not made or inadequate, the result can be expensive repairs, possible loss of prestress in prestressed concrete members and therefore, the concrete structures do not serve for their entire projected design lifetime. Even if the creep analysis of the concrete structure is over-simplified or erroneous, not much trouble may arise during the first years of the service life, but the fact that potential problems may lie further in the future should not delude the designer into paying insufficient attention to the creep phenomenon. In addition, high-strength concrete members are typically more slender than conventional normal-strength concrete members, because of the use of higher strength materials, and because of more refined techniques of design and construction. With a lower ratio of dead to live load, high-strength concrete may be used on much longer spans having smaller flexural stiffness and larger short-term deflections. Under such circumstances the matter of deflections demands special attention. Creep of concrete magnifies the magnitude of the short-term deflection with time. Furthermore, for floor levelness and exterior skin movement in high-rise buildings, creep of cloumns and shear walls can be as important as the strength of concrete. Neglecting the differential compression deformations which occur in the columns of high-rise buildings due to creep can lead to distress in non-load-bearing partitions as well as overstressing of the horizontal elements. Consequently, the design of all creep-sensitive structures requires the ability to estimate the magnitude of creep accurately.

Concrete is a multi-phase composite material, consisting of particles of coarse aggregate embedded in a matrix of mortar. Mortar itself consists of particles of fine aggregate embedded in a matrix of cement paste. The properties of concrete depend on the properties of its component phases and the interaction between them. Most researchers recognize that creep of concrete is closely related to the structure of the hydrated cement paste in the concrete. However, the aggregate, which does not undergo creep only modifies the behavior in a quantitatively important way. This assumption is true for normal-strength concrete under service loads. However, for high-strength concrete its cement paste has strength as high as that of the aggregate, therefore the role of aggregate in creep of concrete is more pronounced and creep takes place in both the cement paste and aggregate in proportion to their individual mechanical and physical properties. Consequently, in order to achieve a better understanding of the mechanism of creep in concrete, a studying of deformations behavior of its individual constituents, that are the mortar and the neat cement paste, is essential.

Moreover, most of the available creep prediction models proposed by the different national building codes, such as ACI Committee 209[1] and CEB-FIP Model Code 1990[2], are valid only for concretes having compressive strengths not greater than 800kgf/cm^2 (80 MPa). On the other hand, higher-strength concretes are regarded as special concretes that are beyond the scope of the recommendations of the model code unless special confirmation of suitability is provided. Consequently, research is needed to eliminate this restriction and a new prediction model for creep which can be used for high-strength concrete is required.

In this paper, a rheological viscoelastic model is proposed for predicting the creep of normal- and high-strength concretes from their basic constituents, that are cement paste and aggregate. This model is based on the assumption that the creep is separated into delayed elastic and flow strains. Furthermore, a parametric study is carried out to compare the creep functions calculated using CEB-FIP Model Code 1990 and ACI Committee 209 with those calculated using the proposed model as well as with the available experimental data. The comparison indicated that the proposed model can predict the creep of both normal- and high-strength concretes.

2. CREEP OF HIGH-STRENGTH CONCRETE

In high-strength concrete, the use of superplasticizers has enabled to reduce the water/cement ratio to the order of 0.20 to 0.30 without sacrificing fluidity of the concrete. Generally, the lower water/cement ratio results in better creep performance, namely, both basic creep and total creep decrease with the decrease in water/cement ratio.

Some creep data on normal-strength concrete are available; however, the structure of high-strength concrete varies significantly with that of normal-strength concrete, thus making direct comparisons invalid. In addition, the published literature contains small amount of data on the creep behavior of high-strength concrete. For example, Nagataki and Yonekura[3],[4] studied the creep characteristics of concretes having compressive strengths in the range of 350 to 1100kgf/cm^2 (35 to 110 MPa). They found that, the specific creep (creep strain per unit stress) of high-strength concrete cured in air was approximately one-third of that of normal-strength concrete. In addition, they concluded that drying creep becomes smaller as compressive strength increases up to about 1000kgf/cm^2 (100 MPa), where it becomes practically zero. Ngab et al., (quoted by ACI Committee 363[5]) found that there is little difference between the creep strains of high-strength concrete under drying and sealed conditions. Russell and Corley[6] and Russell and Larson[7] investigated the time-dependent behavior of columns, walls and caissons in Water Tower Place (262m high reinforced concrete building, Chicago, Illinois). They concluded that, higher strength concrete with compressive strength of 620kgf/cm^2 (62 MPa) had less specific creep than lower strength concrete with compressive strength of 280kgf/cm^2 (28 MPa). Another experimental investigation was carried out by Hwee and Rangan[8] on a commercial high-strength concrete (concrete had a nominal compressive strength of 600kgf/cm^2 (60 MPa) at 56 days) available in Australia. The researchers observed that, high-strength concrete creeps significantly less than normal-strength concrete. In addition, for the concrete tested in their study, the estimated final creep coefficient was 1.35. Additionally, Paulson et al.[9] confirmed that, the creep coefficient for the high-strength concrete with strength in the range of 840kgf/cm^2 (84 MPa) is about half of that of normal-concrete with compressive strength of about 380kgf/cm^2 (38 MPa).

From the above limited experimental investigations on the time-dependent behavior of high-strength concrete, it can be concluded that the specific creep of high-strength concrete is less than that

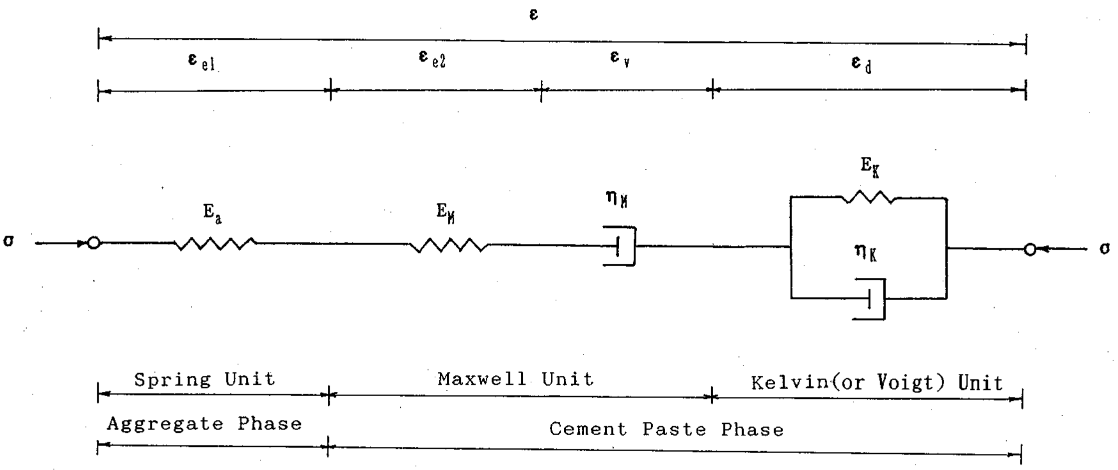

Fig. 1 Proposed Viscoelastic Five-Element Model to Represent the Time-Dependent Behavior of Concrete.

of normal-strength concrete and also high-strength concrete has a smaller drying creep to basic creep ratio.

3. PROPOSED AGING VISCOELASTIC MODEL FOR CONCRETE

A five-element viscoelastic model comprised of a Hookean spring added serially to a Maxwell model and a Kelvin (or Voigt) model is proposed to simulate the creep behavior of concrete subjected to a sustained stress (see **Fig. 1**). In the proposed model, the aging shows itself by the time-dependent variation in the value of the moduli of elasticity and the coefficients of viscosity, elasticity manifests itself by the recoverable deformation after unloading, and viscosity is represented by the capacity of the deformation to develop with time and by the irrecoverable deformation. In this model, the Hookean spring unit represents the deformational characteristic of the elastic aggregate phase, whereas the Maxwell and Kelvin units represent the deformational characteristic of the viscous hydrated cement paste phase of concrete.

The strain response of the proposed model is a sum of responses of its spring, Maxwell and Kelvin units as shown schematically in **Fig. 2** if t_1 is the time of the application of the sustained stress. Accordingly, for this model, there is no strain prior to $t=t_1$, and upon application of the stress there is an instantaneous elastic response corresponding to AB. However, whereas the stress is maintained at a constant value for $t \geq t_1$, the strain steadily increases in a form similar to that shown schematically as curve BCD in **Fig. 2**.

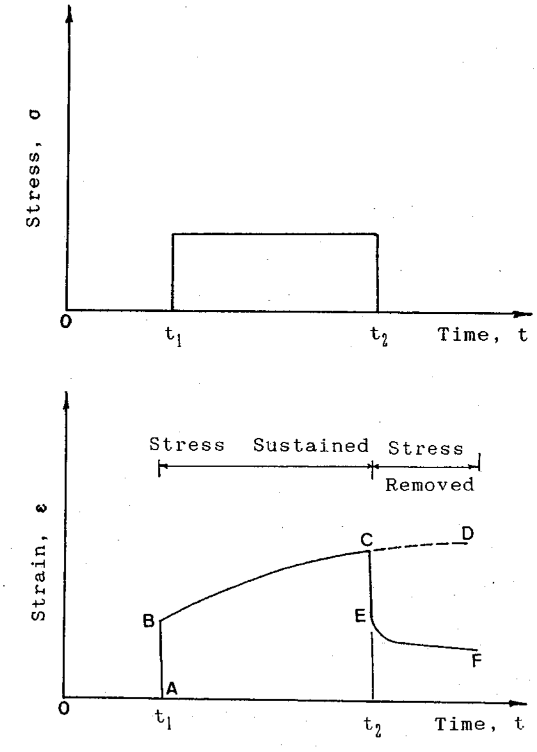

Fig. 2 Stress- and Strain-Time Curves for the Proposed Model

If the stress is removed at some time $t=t_2$ the model will follow a delayed recovery path similar to that shown schematically as CEF in **Fig. 2**. This is made up of an instantaneous elastic component CE followed by a gradual recovery EF. The model will exhibit some permanent residual strain as t tends to infinity because of the aging effect and the flow in Maxwell unit. Consequently, the behavior of the proposed model is qualitatively similar to that of concrete.

For the proposed model illustrated in **Fig. 1**, the total strain ε under a sustained stress σ is

$$\varepsilon=\varepsilon_{e1}+\varepsilon_{e2}+\varepsilon_v+\varepsilon_d \qquad (1)$$

The first and second terms in Equation (1) represent the instantaneous elastic strain components for the aggregate phase and the cement paste phase, respectively. The third term represents the irreversible viscous strain (flow). The last term represents the delayed elastic strain (recoverable creep). The last two terms depend on the duration of load application.

Because of the series combination, the mechanical units have the same stress transmitted through each element, therefore

$$\sigma=\frac{E_a}{V_a}\varepsilon_{e1}=\frac{E_M}{V_{cp}}\varepsilon_{e2}=\eta_M\frac{d\varepsilon_v}{dt}=E_K\varepsilon_d+\eta_K\frac{d\varepsilon_d}{dt} \qquad (2)$$

where

σ : constant applied stress.
V_a : volume concentration of aggregate.
V_{cp} : volume concentration of cement paste.
here, $V_a+V_{cp}=1$
E_a : modulus of elasticity of aggregate.
E_M : spring modulus of Maxwell unit, i.e., the modulus of elasticity of cement paste.
E_K : spring modulus of Kelvin unit.
η_M : viscosity of the dashpot of Maxwell unit.
η_K : viscosity of the dashpot of Kelvin-Voigt unit.
t : duration of sustained stress $(t=t-t_1)$

(1) Rheological Constants for the Proposed Model

It was recognized that, due to aging mechanism, chemical and physical changes occur gradually in the internal microstructure of the concrete. It is usual to consider aging as confined to processes that decrease the energy of the system. This can be interpreted as increasing the strength of bonding within and between the colloidal particles of the hydration products (Young[10)]). Therefore, the properties of concrete change with time and are greatly affected by temperature and relative humidity, and therefore by the environment. As a result, the compressive strength and the modulus of elasticity of concrete increase with its age.

Consequently, in order to obtain a quantitatively good agreement between the deformation of the proposed model and the creep behavior of concrete, the rheological constants of this model should be taken to be of time-dependent type.

a) Maxwell Unit

1) The elasticity of spring element (E_M)

If the concrete (or cement paste) specimen is modeled by a linear elastic spring having time-dependent modulus of elasticity, e.g. at any time (t_i), the spring has an elastic constant equal to $E(t_i)$. When the specimen is loaded and unloaded at the same time, then the instantaneous strain should be elastic (reversible). Whereas, if the loading and unloading ages are different, there is no full elastic recovery due to aging process caused by continued hydration. Accordingly, the above mechanism can be mathematically expressed as follows:

At any time (t_i), the instantaneous strain $\varepsilon(t_i)$ which occurs during the application of stress (or within seconds thereafter) is as follows:

$$\varepsilon(t_i)=\frac{\sigma}{E(t_i)} \qquad (3)$$

where

σ : uniaxial applied stress.
$E(t_i)$: modulus of elasticity of concrete (or cement paste) at age t_1, the time of application of the stress.

The above relation assumed that the applied stress is constant and is proportional to strain in service conditions.

Therefore, the instantaneous elastic strains $\varepsilon(t_1)$ and $\varepsilon(t_2)$ at times t_1 and t_2 respectively are as follows:

$$\varepsilon(t_1)=\frac{\sigma}{E(t_1)},\ \varepsilon(t_2)=\frac{\sigma}{E(t_2)} \qquad (4)$$

And thus the permanent strain due to loading at time t_1 and unloading at time t_2 is calculated by the following relation:

$$\varepsilon(t_1)-\varepsilon(t_2)=\sigma\left[\frac{E(t_2)-E(t_1)}{E(t_1)E(t_2)}\right] \qquad (5)$$

Consequently, the modulus of elasticity of the Maxwell unit should be expressed by

$$E_M=E_M(t_1) \text{ or } E_M(t_2) \qquad (6)$$

where

$E_M(t_1)$: modulus of elasticity at time of loading.
$E_M(t_2)$: modulus of elasticity at time of unloading.

2) The viscosity of dashpot element (η_M)

Because of the progress of hydration of cement paste under load, the viscous element of the Maxwell unit is assumed to be of age-thickening type with infinite viscosity at infinite time. However, as it is generally believed that creep of concrete tends to a finite limit, the law governing the age-dependence of the viscosity of the Maxwell dashpot should be such as to satisfy this requirement. Therefore,

$$\eta_M=a_1\exp[a_2(t-t_1)] \qquad (7)$$

where a_1 and a_2 are parameters depending on the properties of cement paste.

The parameter a_1 represents the viscosity at time t_1, whereas the parameter a_2 governs the rate of increase of cement paste viscosity with time. Needless to say, the coefficient of viscosity η_M must increase with a decrease in the water-cement ratio.

Table 1 Proposed Values of the Rheological Constants

Const.	$\sigma_{c28} \leq 420$		$\sigma_{c28} > 420$								
	$t_1 = 3$ or 7	$t_1 = 14$ or 28	$t_1 = 3$			$t_1 = 7$			$t_1 = 14$ or 28		
			$t - t_1$								
			< 1000	1000~2000	> 2000	< 1000	1000~2000	> 2000	< 500	500~1000	> 1000
E_K	$1.50\ Ec_{28}$	$1.85\ Ec_{28}$	$0.70\ Ec_{28}$	$1.40\ Ec_{28}$	$1.85\ Ec_{28}$	$0.80\ Ec_{28}$	$1.40\ Ec_{28}$	$2.0\ Ec_{28}$	$1.50\ Ec_{28}$	$2.0\ Ec_{28}$	$2.50\ Ec_{28}$
$\alpha_1 \alpha_2$	$0.50\ Ec_{28}$	$0.65\ Ec_{28}$	$0.50\ Ec_{28}$			$0.70\ Ec_{28}$			$0.30\ Ec_{28}$	$0.50\ Ec_{28}$	$0.70\ Ec_{28}$
α_2	0.01		0.001								
β	0.164										

MPa = 10.2 kgf/cm^2

t_1 : age of concrete when the load is first applied in days.

$t - t_1$: duration of sustained loading in days.

σ_{c28} : concrete compressive strength at the age of 28 days in kgf/cm^2.

Ec_{28} : secant modulus of elasticity at 0.40 σ_{c28} and at the age of 28 days in kgf/cm^2

b) Kelvin Unit

In the Kelvin-Voigt unit the ratio E_K/η_K in the exponential term should be a time-dependent. However, since the Kelvin unit has an asymptotic strain value at infinite time, thus the viscous element in this unit may be assumed proportional with square root of time as follows:

$$\eta_K = \frac{1}{\beta} E_K (t - t_1)^{0.5} \tag{8}$$

where

β : a coefficient governing the change in the ratio E_K/η_K.

E_K : elastic constant of the Kelvin spring element.

(2) Rheological Equation of the Proposed Model

Using the above rheological constants outlined by Equations (6), (7) and (8), the strain components of Equation (1) can be constructed as follows by solving the differential equations:

$$\varepsilon_{e1} = \frac{\sigma V_a}{E_a}$$

$$\varepsilon_{e2} = \frac{\sigma V_{CP}}{E_M(t_1)}$$

$$\varepsilon_v = \frac{\sigma}{\alpha_1 \alpha_2} [1 - \exp(-\alpha_2 (t - t_1))]$$

$$\varepsilon_d = \frac{\sigma}{E_K} [1 - \exp(-2\beta (t - t_1)^{0.5})]$$

Thus, the rheological equation of the proposed model is

$$\varepsilon = \sigma \left[\frac{V_a}{E_a} + \frac{V_{CP}}{E_M(t_1)} + \frac{1 - \exp(-\alpha_2 (t - t_1))}{\alpha_1 \alpha_2} + \frac{1 - \exp(-2\beta (t - t_1)^{0.5}}{E_K} \right] \tag{9}$$

And the creep compliance (or the creep function) is given by

$$\frac{\varepsilon}{\sigma} = \frac{V_a}{E_a} + \frac{V_{cp}}{E_M(t_1)} + \frac{1 - \exp(-\alpha_2 (t - t_1))}{\alpha_1 \alpha_2} + \frac{1 - \exp(-2\beta (t - t_1)^{0.5})}{E_K} \tag{10}$$

As t becomes infinity, the ultimate creep strain in the proposed model approaches the value

$$\varepsilon_{C\infty} = \sigma \left[\frac{1}{\alpha_1 \alpha_2} + \frac{1}{E_K} \right] \tag{11}$$

If the load is removed at time t_2, the instantaneous elastic strain recovery ε_{ir} is

$$\varepsilon_{ir} = \sigma \left[\frac{V_a}{E_a} + \frac{V_{CP}}{E_M(t_2)} \right] \tag{12}$$

For the Kelvin unit, the deformation will recover in accordance with the pattern expressed by the following equation when the stress is removed at time t_2:

$$\varepsilon_{dr} = \varepsilon_d(t_2) [1 - \exp\{-2\beta (t - t_2)^{0.5}\}] \tag{13}$$

Therefore, the delayed elastic strain ε_{dr}, after time t_2 is

$$\varepsilon_{dr} = \frac{\sigma}{E_K} [\exp(-2\beta \sqrt{t - t_2}) - \exp\{-2\beta (\sqrt{t_2 - t_1} + \sqrt{t - t_2})\}] \tag{14}$$

and the permanent residual strain ε_P is

$$\varepsilon_P = \sigma \left[V_{CP} \frac{E_M(t_2) - E_M(t_1)}{E_M(t_1) E_M(t_2)} + \frac{1 - \exp(-\alpha_2 (t_2 - t_1))}{\alpha_1 \alpha_2} \right] \tag{15}$$

The values of α_1, α_2, β and E_K can be determined experimentally using the optimization techniques with data of strain corresponding to elapsed time of sustained load obtained from results of creep test. On the other hand, $E_M(t_1)$ can be obtained from modulus

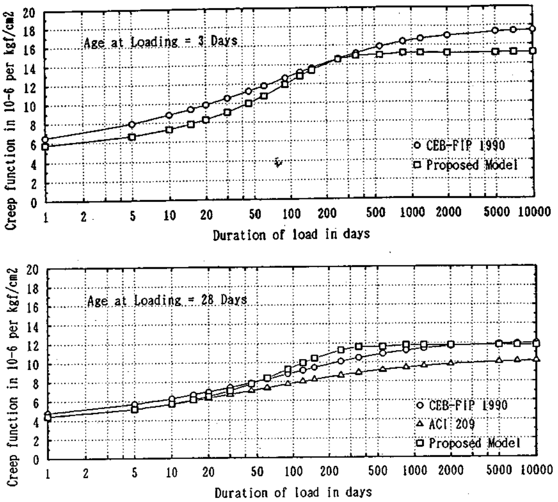

Fig. 3 Creep Function Curves for Concrete Having a Compressive Strength Equal to 300 kgf/cm² (30 MPa)

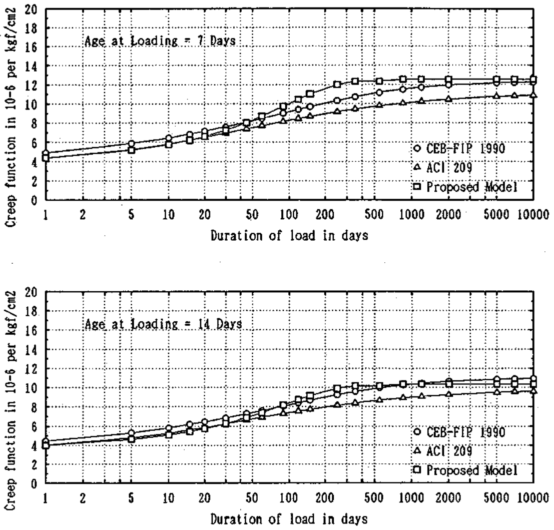

Fig. 4 Creep Function Curves for Concrete Having a Compressive Strength Equal to 400 kgf/cm² (40 MPa)

of elasticity test at the time of loading and $E_M(t_2)$ can be determined from the immediate recovery strain after unloading in creep test or from the expressions of modulus of elasticity at any age given by the standard building codes.

4. PARAMETRIC STUDY

Since the actual creep testing is a long term process, the rheological constants of the proposed model is primarily estimated from the expected values of the delayed elastic strain and the ultimate creep strain. Thereafter, a parametric study for modification of the primary rheological constants is implemented. In the parametric study, the effect of age at load application and duration of loading as well as the compressive strength of concrete are investigated. Other factors such as ambient relative humidity, temperature, type of cement, etc. are considered constant in this study. **Table 1** illustrates the rheological constants obtained by trial and error to fit the creep function results predicted by CEB-FIP Model code 1990 and ACI Committee 209.

5. COMPARISON BETWEEN THE PROPOSED MODEL AND THE STANDARD MODE CODES

Figs. 3 to 8 show the comparison between the creep functions calculated using the proposed model with those predicted using the CEB-FIP 1990 model code and the ACI committee 209. The following values were considered in these comparisons:

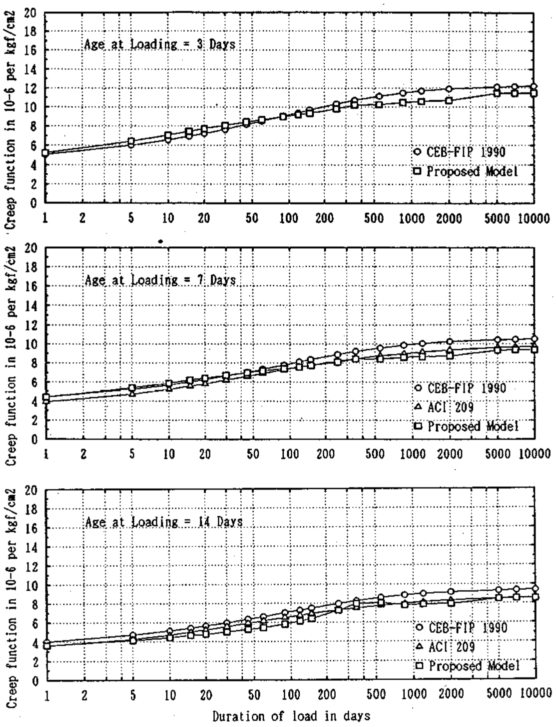

Fig. 5 Creep Function Curves for Concrete Having a Compressive Strength Equal to 500 kgf/cm² (50 MPa)

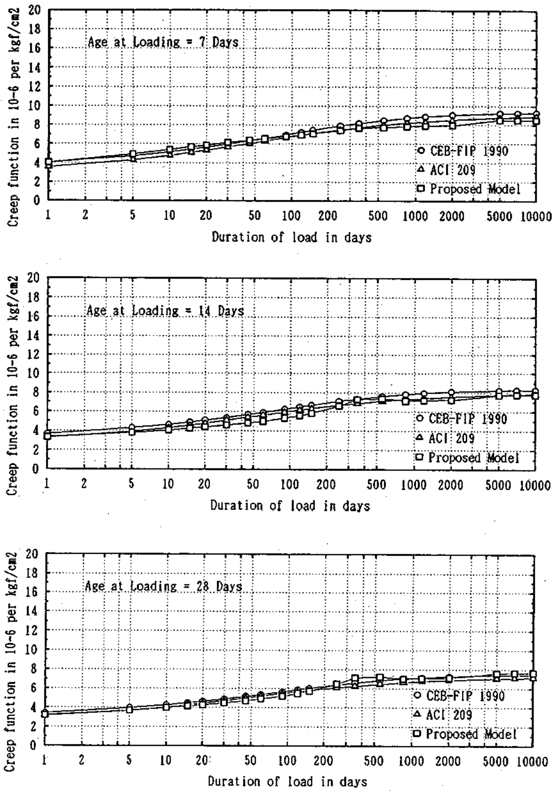

Fig. 6 Creep Function Curves for Concrete Having a Compressive Strength Equal to 600 kgf/cm² (60 MPa)

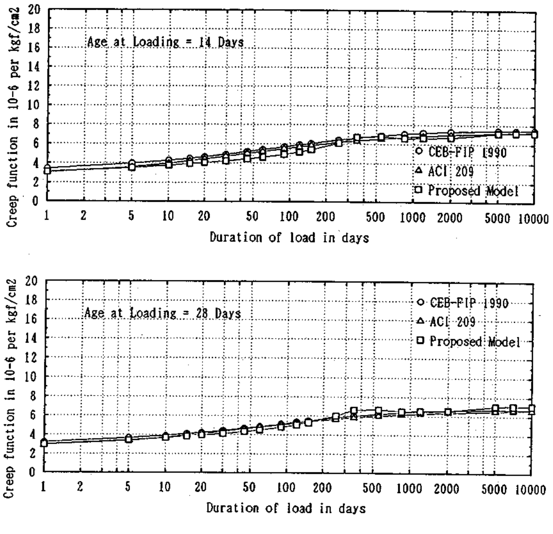

Fig. 7 Creep Function Curves for concrete Having a Compressive Strength Equal to 700 kgf/cm² (70 MPa)

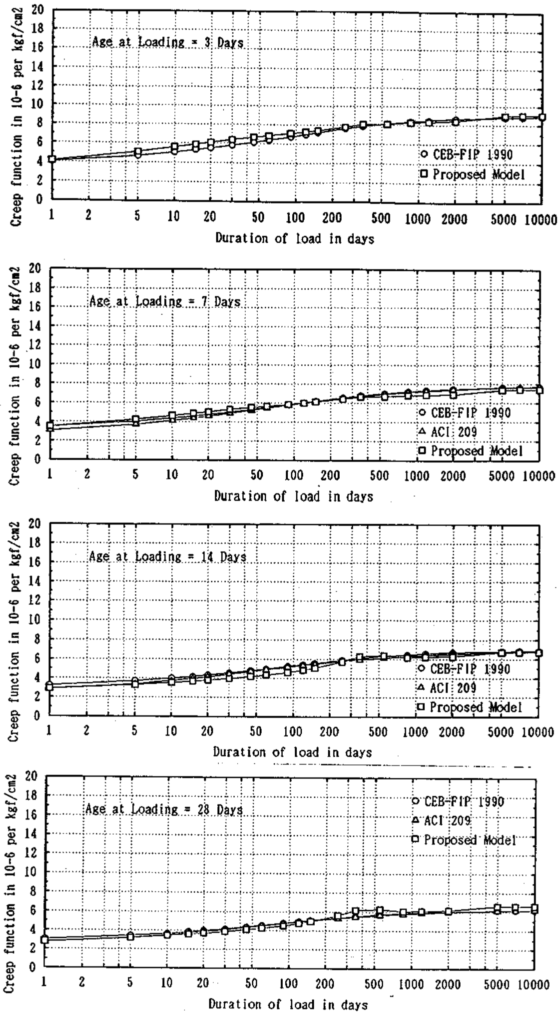

Fig. 8 Creep Function Curves for Concrete Having a Compressive Strength Equal to 800 kgf/cm² (80 MPa)

t_1 =3, 7, 14, and 28 days.

$t-t_1$ =1, 5, 10, ..., 7000 and 10000 days.

σ_{c28} =300, 400, 500, 600, 700 and 800 kgf/cm² (30 to 80 MPa).

It should be noted that for moist cured concrete the age of concrete at loading in the ACI method must be ≥ 7 days. Also, the values of the creep function at any time are given in 10^{-6} per kgf/cm² (10^{-5} per MPa). From detailed examination of **Figs. 3** to 8, it can be concluded that the proposed model can predict the creep of both normal- and high-strength concretes. Furthermore, **Table 2** shows that, the specific creep for high-strength concrete with strength of about 800 kgf/cm² (80 MPa) is about half of that of normal-strength concrete with compressive strength of

Table 2 Specific Creep Values of the Proposed Model

Age at Loading (days)	Duration of Load (days)	Specific Creep in 10^{-6} per kgf/cm^2 (10^{-5} per MPa)					
		Concrete Compressive Strength in kgf/cm^2 (MPa)					
		300 (30)	400 (40)	500 (50)	600 (60)	700 (70)	800 (80)
3	30	4.11	3.56	3.21	2.93	2.72	2.54
	90	6.97	6.04	3.90	3.56	3.30	3.08
	350	9.96	8.63	4.94	4.51	4.18	3.91
	1000	10.1	8.82	5.36	4.90	4.53	4.24
	10000	10.2	8.83	5.71	5.21	4.83	4.52
28	30	3.25	2.81	1.94	1.77	1.64	1.53
	90	5.46	4.73	2.74	2.50	2.31	2.16
	350	7.77	6.73	4.88	4.46	4.13	3.86
	1000	7.94	6.88	5.23	4.77	4.42	4.13
	10000	7.95	6.90	5.42	4.94	4.58	4.28

about 300 kgf/cm^2 (30 MPa). This results are fairly agreed with the available experimental data on high-strength concrete.

6. CONCLUSIONS

Based on the study of this paper, the following conclusions are offered:

(1) An aging rheological viscoelastic model is proposed and used to predict the creep of concrete. In this model, a Hookean spring unit is used to represent the deformational characteristic of the aggregate phase, whereas Maxwell and Kelvin units are used to represent the deformational characteristic of the viscous hydrated cement paste phase of concrete.

(2) In the proposed model, the rheological parameters α_1, α_2 and E_K change for different values of age at loading, duration of load and compressive strength of concrete. On the other hand, the parameter β which governs the change in the ratio E_K/η_K has a constant value.

(3) Comparison of the obtained results from the proposed model with those calculated using CEB-FIP 1990 and ACI 209 models indicated that the proposed model can predict the creep of normal- and high-strength concretes.

(4) Specific creep values calculated using the proposed model are fairly confirmed with available experimental results.

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REFERENCES

1) ACI Committee 209: "Prediction of Creep, Shrinkage and Temperature Effects in Concrete Structures" *ACI SP 76-10, Designing for Creep and Shrinkage in Concrete Structures.* American Concrete Institute, Detroit, Michigan, pp. 193-300, 1982.
2) CEB-FIP Model Code 1990: *CEB -First Draft- Bulletin D'Information No. 195*, Comite Euro-International du Beton, Paris, France.
3) Nagataki, S. and Yonekura, A.: *Properties of Drying Shrinkage and Creep of High-Strength Concrete.* Transactions of The Japan Concrete Institute, Vol. 4, pp. 223-236, 1982.
4) Nagataki, S. and Yonekura, A.: *The Mechanisms of Drying Shrinkage and Creep of Concrete.* Transactions of The Japan Concrete Institute, Vol. 5, pp. 127-140, 1983.
5) ACI Committee 363: *State-of-the-Art Report on High-Strength Concrete.* ACI Journal, Proceedings Vol. 81, No. 4, pp. 364-411, 1984.
6) Russell, H.G. and Corley, W.G.: "Time-Dependent Behavior of Columns in Water Tower Place". *ACI SP 55-14, Douglas McHenry International Symposium on Concrete and Concrete Structures*, Edited by B. Bresler. American Concrete Institute, Detroit, Michigan, pp. 347-373, 1978.
7) Russell, H.G. and Larson, S.C.: *Thirteen Years of Deformations in Water Place.* ACI Structural Journal, Proceedings Vol. 86, No. 2, pp. 182-191, 1989.
8) Hwee, Y.S. and Rangan, B.V.: *Studies on Commercial High-Strength Concretes.* ACI Materials Journal, Proceedings Vol. 87, No. 5, pp. 440-445, 1990.
9) Paulson, K.A., Nilson, A.H. and Hover, K.C.: *Long-Term Deflection of High-Strength Concrete Beams.* ACI Materials Journal, Proceedings Vol. 88, No. 2, pp. 197-206, 1991.
10) Young, J.F.: "Physical Mechanisms and their Mathematical Descriptions", Chap. 1, *Mathematical Modeling of Creep and Shrinkage of Concrete*, Edited by Z. P. Bazant, pp. 63-98, John Wiley and Sons Ltd., 1988.

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高強度コンクリートを志向したコンクリートのクリープの予測

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高強度コンクリートを志向したコンクリートのクリープの予測のための新しい粘弾性モデルを提案した．このモデルは，遅れ弾性ひずみとフローひずみの中に，セメントの水和の増進によるコンクリートの物性の変化を考慮したところに特徴がある．本モデルを用いてクリープ関数を計算した結果，CEB-FIP モデルおよび ACI モデルと良い対応を示し，提案したモデルが両モデルに含まれていない高強度コンクリートのクリープについて予測できる可能性が示された．