STUDY ON TENSILE CREEP OF CONCRETE AT AN EARLY AGE

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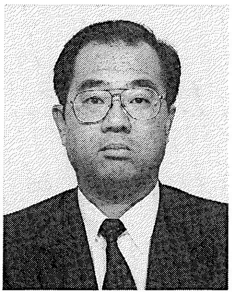
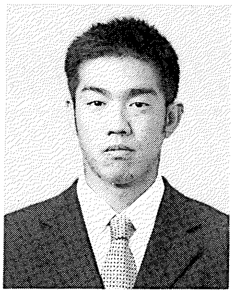
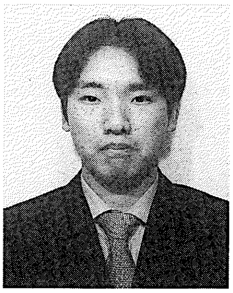
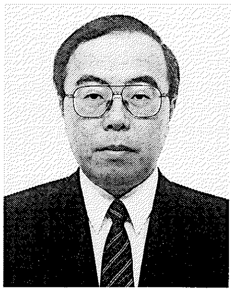

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The effects of stress-strength ratio, loaded age, and temperature during curing and loading on the tensile creep of concrete at an early age are elucidated on the basis of tensile creep experiments. Furthermore, the applicability of a formula for thermal stress analysis was investigated by comparison with the experiment data, which simulate thermal stress conditions. It is noted that the effects of stress-strength ratio are significant and that the effects on creep strain can be defined as exponential function. The effects of loading age were of little significance, although an effect was noted in one-day loading. Regarding the effects of temperature, creep increased as temperature rose. The effect was formulated based on Arrenius's Formula and the activation energy was 83.71J/mol. Super-position was used to account for changing stress and temperature conditions such as thermal stress, and the formula was well able to simulate the experiment data.

Key Words: *tensile creep, early age, thermal stress, stress- strength ratio, equivalent hydration period*

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1. INTRODUCTION

A study on predicting the hydration – induced thermal stress of cement to high accuracy at every stage of construction from planning to construction has been carried out. As a result, it is possible to develop effective countermeasures and avoid serious cracking in structures. The most effective requirement is prediction with high accuracy during the design of a structure. An analytical system for prediction is required. Since failure to take creep into account reduces accuracy, the authors have been the developing a creep function for early age concrete which is applicable to such prediction [1],[2],[3].

Serious stress which may induce cracking that penetrates the thickness of a member is caused by constraint imposed by previously concreted members. A typical pattern of stress generation is that compressive stress first arises in correspondence with temperature rise, and this stress is relieved and converted to tensile stress as temperature decreases again. Consequently, a study of compressive creep, tensile creep, and creep during the unloading process, which simulates changing thermal stress, is needed for application to prediction. The age considered is up to 7 days, since this stress is closely related to cement hydration. Since effects of loading and temperature are more significant at an early age, when the cement hydrates rapidly, than during matured age, a study focuses on loaded age, temperature, and stress-strength ratio. The authors have already presented results of parametric creep studies at an early age, such as compressive creep [1] and creep during the unloading process [2]. They have also described a creep model which is applicable to the prediction of thermal stress. Further, they have shown the difference between compressive and tensile creep based on experiments at the same condition [3].

In this paper, the effects of loaded stress and both curing and loading temperature on tensile creep are investigated with the aim of predicting thermal stress. An additional investigation is carried out on the effect of creep strain on tensile failure in order to estimate the influence creep on generation crack. Finally, a creep model is introduced and results obtained with it are compared to experimental results designed to simulate thermal stress.

2. RESULTS OF PREVIOUS TENSILE CREEP STUDIES

Although tensile creep has a significant effect on the cracking of concrete, little published data is available because of difficulties in carrying out experiments and measurements. However, several papers recently appeared as technology progress. These previous findings were surveyed in order to assess the state of the art as regards tensile creep, and the results were categorized into individual effects.

Although the authors have pointed out that the major component of creep is generated in the cement paste [1], P.L.Dononne noted that tensile creep strain increases in correspondence with volume of paste [4]. He pointed out furthermore that the effect of water - cement ratio is relatively small compared to compressive creep. The authors have also presented the results of tensile creep experiments, in which the volumes of mortar and coarse aggregate were parameters. Tensile creep strain was shown to be proportional to the volume of paste under the same experimental condition [3]. They also pointed out that tensile creep strain is affected significantly by the volume of coarse aggregate.

J.Nishibayashi discussed the effects of aggregate type based on creep experiments in which the creep strain of concrete with light-weight aggregate was found to be 2.4 times greater than with normal aggregate when loaded at 28 days. These results mean that tensile creep strain is influenced by both the volume and type of aggregate.

Regarding the water cement ratio according to research by P.L.Donomonne, the creep strain increases with rising water - cement ratio which dominates pore structures of cement paste which influence creep mechanism [4]. Since E.L.Baroudy presented similar results, it is clear that creep strain does indeed increase with water - cement ratio [6]. This tendency was observed in compressive creep. It is noted that the effect of water - cement ratio is large in tensile creep, and that it dominates pores structure of cement paste. However the mechanism by which the pore structure affects tensile creep has not been identified.

Regarding the effect of loaded age, creep strain of light-weight concrete loaded at 7 days is 6~10% and 7~11% greater, respectively, than that of concrete loaded at 28 days and 91 days, according to results by M.Kakizaki who has studied the tensile creep of concrete containing artificial light weight aggregates [7].

S.Nishibayashi showed that the tensile creep strain of normal and light weight concrete loaded at 7 days is much greater than that loaded at 28 days [5]. It is noted that creep strain decreases with loaded age. However authors pointed out as a result of tensile creep experiments in which the loaded age was less than 7 days that tensile creep didn't significantly depend on loaded age but depended on stress-strength ratio [8]. The effect of increment of strength decreases with loading age in case that stress-strength is constant [8]. In the case of a constant stress-strength ratio, this means that the effect of falling creep strain corresponding to increased loaded age by stiffening the cement paste, the increment is compensated by increment of loading stress. The authors noted that the effects of stress-strength ratio are significant in compressive creep, since the matrix of cement paste has little stiffness at an early age [1]. However A.Gutsch presented results of tensile mechanical behavior experiments with several cements and curing temperatures, showing that tensile creep strain depended on stress-strength ratio, although tensile creep was closely related to hydration. He also pointed out that hydration has little observable effect on tensile creep [9]. D.W. Hobbs has also shown that tensile creep under drying conditions has no influence from stress-strength ratio using the tensile creep tests by the shrinkage constraint method under dry conditions [10]. D.J.Cook pointed out that tensile creep strain was linear to the stress-strength ratio from 25 % to 67 % [11]. A.M.Neville showed that tensile creep strain was linear to stress-strength ratio up to 50 %, but it rapidly increased beyond that point [12]. N. Hauggaard pointed out that creep strain at an early age was linear to stress-strength ratio based on experiments [13].

Recovery behavior after tensile stress unloading is also important. D.Morin showed that no tensile creep recovery occurred based on the results of tensile creep tests with normal and light-weight concrete [14]. The authors demonstrated that strain recovery after tensile stress unloading was small and independent of stress-strength ratio, although some recovery was observed.

H.Morimoto pointed out that compressive and tensile relaxation at an early age was linear to stress-strength ratio based on constraint relaxation experiments. It is also quite important to assess how creep affects cracking and therefore creep failure. M.Kakizaki showed that light-weight concrete creep failure was observed 2 hours after loading at a stress-strength ratio of 80 % [8]. Al.Kubaisy pointed out that at maturity creep failure was observed at strength – stress ratios above 70% as result of experiments with ratio 60% to 95% [16]. It should be noted that little published data is available on tensile creep at an early age, although many studies are in progress.

In this paper, several factors affecting creep, such as loaded age, stress-strength ratio, curing temperature, and loading temperature are quantitatively assessed through tensile creep experiments at an early age, and a tensile creep model for concrete at an early age is presented.

3. PROCEDURE OF TENSILE CREEP EXPERIMENTS

(1) Materials and mix proportion

The mix proportion used for this experiment was selected from candidates commonly used in actual reinforced concrete work in NAGOYA and it has a compressive strength of used 30N/mm^2, a water cement ratio of 40%, and a sand ratio of 44.6%. Details of material are given in **Table** 1 and the mix proportion is illustrated in **Table** 2.

(2) Specimens and loading condition

Concrete was mixed in a temperature controlled laboratory at 20℃ and cast in molds before storage under the same conditions for 24 hours. Specimens were then demolded and immediately sealed with an aluminum membrane in order to avoid diffusion of moisture. Specimen were cured in a temperature - and moisture - controlled room at 30 ℃ and 98%

Table 1 Materials of Concrete

Material	Type and Origine	Specific weight
Cement	OPC	3.15
Fine aggregate	Mountain sand	2.55
Coarse aggregate	Gravel	2.65 Gmax=20mm
Admixture	Water reducing	1.1

Table 2 Mix-proportion

Slump (cm)	Air (%)	W/C (%)	s/a (%)	Unit weigh (kg/m^3) W	C	S	G	AD
8.0	4.0	55.0	44.6	172	313	787	1015	1.16

RH until loading, which took place at 1 to 7 days. This temperature was chosen because the experiment was carried out during summer; the temperature - controlled enclosure for the creep test apparatus could be kept continuously below the ambient temperature. However, the temperature for assessing curing and loading temperature effects was set at 30℃ to 50℃. The creep test apparatus was of lever type with a temperature and humidity controlled enclosure in the loading area [1]. Humidity of every case was controlled at 98%. The strain of an unloaded specimen made under the same condition was measured in order to compensate for shrinkage not caused by creep, such as automogenous shrinkage so on. Creep strain is calculated by extracting the measured strain of the unloaded specimen from the strain of the loaded specimen. Tensile strength at the loading age, which was needed to calculate the stress-strength ratio, was measured by a splitting test on an unloaded specimen cured under the same conditions as the loaded ones. The relationship between tensile strength and maturity is defined by the following formula:

$$f_t(M)=0.49\ln(M) - 2.05 \quad (1)$$

Where, $f_t(M)$: tensile strength at maturity M ;
and M : maturity (degree·hour)

(3) Loading procedure

Loading was by pulling on the attachments fixed to the top and bottom of the specimen by bolts [2]. Although this creep test apparatus is able to directly apply tensile stress by means of a lever, but a bending moment might be generated due to shifting of the loading axis from the center of the specimen due to creep deformation. An automatic adjusting system was added to compensate for this effect. Since the embedded bolts for the pulling attachment might lead to failure at the bolt at an early age, such as 1 day, and at high stress-strength ratios such as 60%, a dog bone specimen was used for such cases. Details of the dog bone specimen are given in **Fig.**1 and the equipment for attachment is shown in **Fig.** 2.

(4) Strain measurements

Embedded strain meters modified to take measurements of concrete at an early age were used for creep strain. Since the center section of the dog bone specimens is only 75 mm in diameter, the meter was improved to a more slender type in this case. This slender strain meter is shown in Fig.3. It was checked that these strain meter and specimen modifications caused no difference in measured strain under the same conditions. Since difference of strength and creep behavior is influenced by hydration rates, two specimens were tested at any case, and a measured creep strain was defined as the mean value.

(5) Experimental cases

The experimental cases are shown in Table 3. The effect of stress-strength ratio (S/S) was investigated in

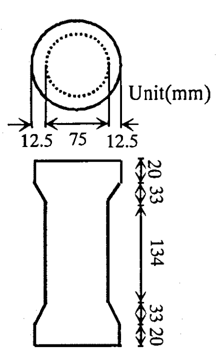

Fig.1 Dog-Bone Typed Specimen

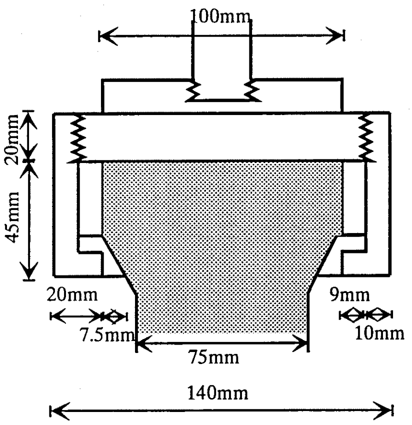

Fig.2 Attachment for the dog-bone specimen

cases 1 to 17, the effect of curing temperature until 3 days and loading temperature in cases 18 to 26, and the effect of curing temperature and loading temperature at 5 days in cases 27 to 35. The loading period was basically 5 days.

4 RESULTS OF EXPERIMENTS AND DISCUSSION

(1) Effects of loading period

The relationship between creep strain and loading period for S/S=50% and a loading age of 3 days is shown in **Fig.**4. Although creep strain increased significantly for the 3 days after loading, it reached a steady state at 5 days. The loading period was chosen to be 5 days in this study, since creep strain at an early age is affected significantly by several factors during this period. Thus, creep strain at 5 days is defined as the final creep strain in this study. However changes beyond 5 days are taken into account in the creep model.

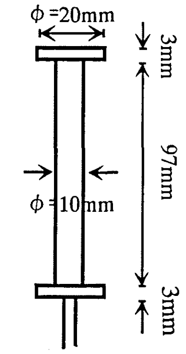

Fig.3 Strain meter for dog-bone Specimen

(2) Effects of stress - strength ratio

The relationships between creep strain with loading at 1, 3, and 5 days for several S/S value are shown in **Figs.**5 ~ 7. Creep strain at early period immediately increase after loading and its increment is significant as at an early age and at high stress-strength ratio. The relationship between stress-strength ratio and final creep strain at several loading ages is shown in **Fig.** 8. No linear relationship passing through the zero point is obtained in **Fig.**8 up to S/S=40%. Creep strain at 1 day loading is larger than other ages at lower S/S values and the effect of S/S is not significant. Creep strain increases at 40% of S/S value in cases of loading at 3, 5, and 7 days.

Final creep strain is strongly influenced by the stress-strength ratio in this study. Although tensile creep strain decreases with rising loading age, it is almost similar at other loading ages except 1 day in **Figs.**8, 9, and 10. And the effect of loading age becomes smaller at higher S/S values in **Fig.**8. Loading stress increases with constant stress-strength ratio as loading age increases, since strength increases with age. Besides, creep decreases with rising loading age, since the matrix of cement paste hydrate

Table. 3 Cases of the experiments

Case No.	Loading age (day)	S/S (%)	Curing temp (℃).	Loading temp. (℃).
1	1	10	30	30
2	1	20	30	30
3	1	40	30	30
4	1	60	30	30
5	1	70	30	30
6	3	20	30	30
7	3	40	30	30
8	3	50	30	30
9	3	60	30	30
10	3	70	30	30
11	5	20	30	30
12	5	40	30	30
13	5	50	30	30
14	5	60	30	30
15	5	70	30	30
16	7	20	30	30
17	7	40	30	30
18	14	40	30	30
19	3	40	30	30
20	3	40	30	40
21	3	40	30	50
22	3	40	40	30
23	3	40	40	40
24	3	40	40	50
25	3	40	50	30
26	3	40	50	40
27	3	40	50	50
28	5	40	30	30
29	5	40	30	40
30	5	40	30	50
31	5	40	40	30
32	5	40	40	40
33	5	40	40	50
34	5	40	50	30
35	5	40	50	40
36	5	40	50	50

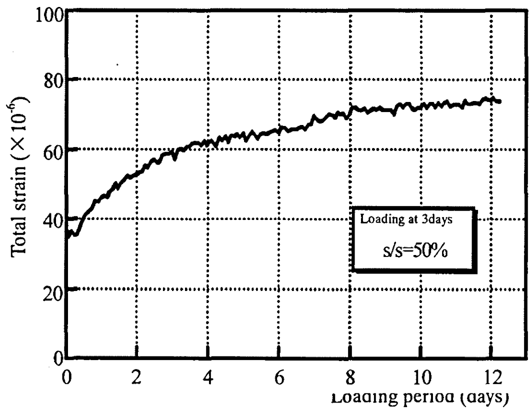

Fig.4 Total strain

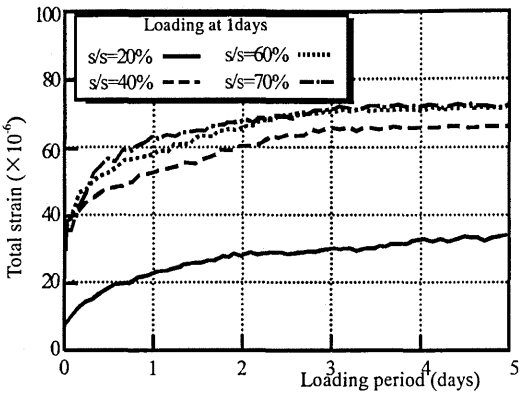

Fig.5 Effect of stress-strength ratio

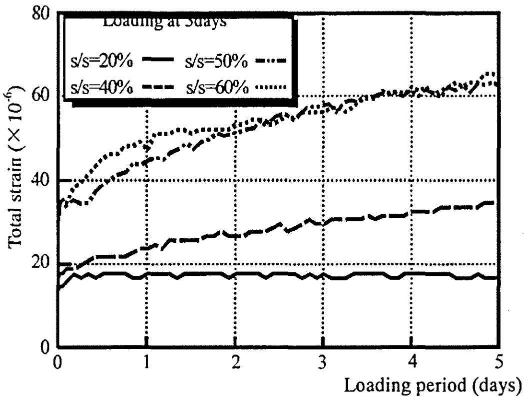

Fig.6 Effect of Stress-strength ratio

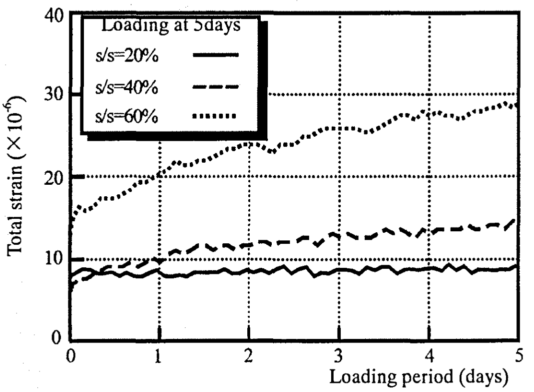

Fig.7 Effect of Stress-strength ratio

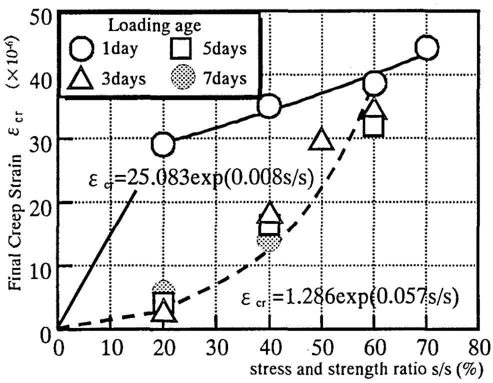

Fig.8 Stress-strength ratio and final creep strain

becomes rigid as hydration progresses. The fall in creep strain with increasing loading age is nearly equal to the rise in loading stress due to hydration. This assertion is supported by **Fig.**9, in which the relationship between loading stress and final creep strain is shown for several loading ages. The final creep strain decreases at greater loading ages in the case of loading at the same stress.

It can be concluded that factors which dominate the fall in tensile creep affect the rise in tensile strength as hydration progress and that both phenomena are caused by the rigidity of the cement paste matrix. Although the effect of loading age is insignificant at S/S values of more than 60%, the creep strain might reach to the deformation limit at these higher S/S ratios. It can be concluded that effect of deformation limit is more significant than effect of loading age. Creep failure might occur at such S/S ratios, if the stress were continuous. Although creep failure is described later, the possibility of creep failure is supported by the fact that tensile creep specimens failed within a day after loading at S/S=70% ~ 80%. The effect of stress-strength ratio at one day is smaller than at other loading ages and the final creep strain is smaller in this case.

Although creep strain is mainly generated by seepage of pore water of cement paste on compressive creep at a matured age, it is considered that creep strain is generated by defective zone and micro cracking at an early age due to weakness of cement paste. Since the results above mentioned show that large creep strain is generated with independence on stress-strength ratio in loading age of 1 day, defective zone might cause creep deformation upon tensile creep at an early age. The mechanism of tensile creep generation at one day is asserted slightly different from that at other ages.

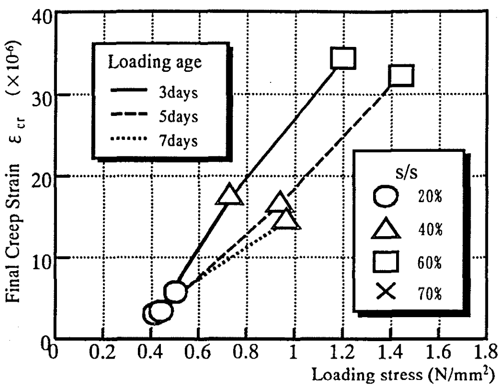

Fig.9 Loading stress and final creep strain

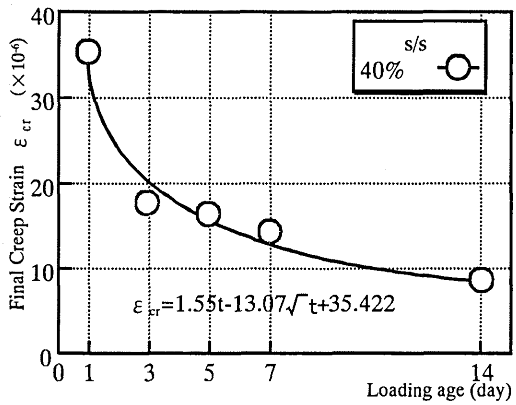

Fig.10 Loading age and final creep strain

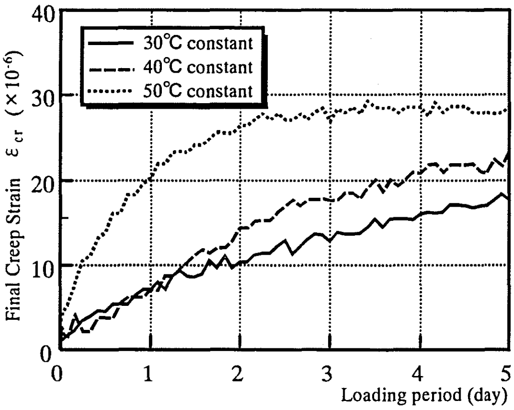

Fig.11 Effect of constant temperature
(Loading at 3 days)

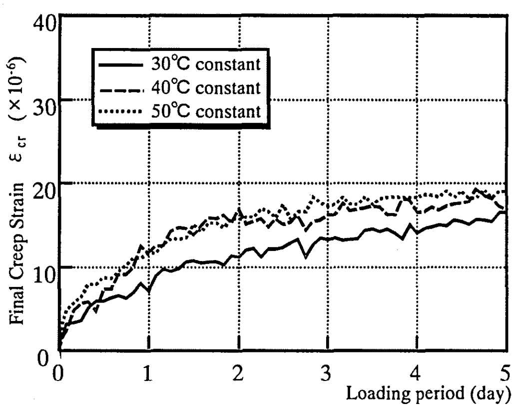

Fig.12 Effect of constant temperature
(Loading at 5 days)

(3) Effect of loading age

The relationship between final creep strain at loading temperature of 30℃, 5 days of loading at S/S=40% is shown in **Fig.**10. Although the final creep strain decreases with higher loading ages, this change in final creep strain is significant from 1 day to 3 days for loading ages but decreases after 3 days at S/S=40%. The reason why significant changing of final creep strain is not observed after 3 days is that the stress-strength ratio is fixed. Although the final creep strain decreases with loading age, the ratio of decrement gradually becomes small due to progress hydration. Although the final creep strain decreases with increasing loading age after 3 days at the same loading stress, it doesn't significantly decrease at same stress-strength ratio. The reason is considered that loading stress increases with loading age due to progress in strength development. Effect of loading age is described in detail in the next section on the effect of temperature.

(4) Effects of temperature

a) Effect of steady temperature

Tensile creep tests were carried out with fixed curing and loading temperatures of 30℃ 40℃ and 50℃, in order to assess a simplified temperature effect. Loading ages were 3 and 5 days and the stress-strength ratio was a constant 40%. Since strength of specimens at loading was different due to different curing temperatures, loading stress was different due to fixing stress-strength ratio. Changes in creep strain during loading are shown in **Figs.**11 ~12. Tensile creep accelerates with loading temperature since the creep strain increases with rising temperature in the case of loading at 3 days. Although the creep strain also increased with loading temperature in the case of loading at 5 days, this temperature effect is smaller than in the case of loading at 3 days. It is noteworthy that creep strain is influenced by temperature when a steady temperature is held throughout curing and loading, and this effect is significant at an early age.

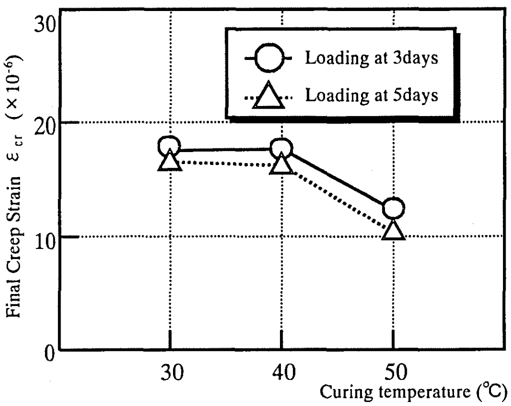

Fig.13 Effect of curing temperature

Although curing and loading temperature were fixed in this section, both temperature values individually affect creep strain. The same effects as accelerating loading age may be observed at high curing temperature. However, the generation of creep strain may be accelerated in high loading temperature since higher loading temperature decreases the viscosity of the pore water of cement hydrates whose seepage causes creep strain [1]. Temperature effects were investigated as described below through creep tests at fixed curing temperatures and several loading temperatures, and also through tests at fixed loading temperature and several curing temperatures.

b) Effect of curing temperature

The relationship between curing temperature and final creep strain is shown in **Fig.**13. These are the results of a parametric study using various curing temperatures and a fixed loading temperature of 30℃. The difference between a curing temperature of 30℃ and 40℃ is little in the case of loading at 3 and 5 days, since the curing period is short. However, the final creep strain after curing at 50℃ is much smaller than in other cases. The final creep strain after loading at 5 days is smaller than that at 3 days. It is observed that final creep strain becomes small by curing at high temperature and by extending the curing period in this experiment which was tested at 40% of S/S. The effect of curing temperature was assessed by modifying the concept of equivalent hydration period as presented by Z.P.Bazant for 25℃ to suit the 30℃ condition of this test [17].

The concept of effective age, which is commonly used in assessing for temperature effects in thermal stress analysis, was adjusted. Equivalent hydration period and effective age are described as follows.:

$$t_{eq} = \Sigma \{ \exp [4000 \left(\frac{1}{271+T_0} - \frac{1}{271+T} \right) \} \triangle t \qquad (2)$$

T_{eq} : Equivalent hydration period
t : Loading period
T_0 : Standard temperature (30℃)
T : Loading temperature(℃)

:

$$t_{eff} = \frac{\Sigma (T + 10) \triangle t}{30} \qquad (3)$$

t_{eff}: Effective age (days)

The relationship between equivalent hydration period, effective age, and final creep strain is shown in **Figs.**14 and15 for the 30℃ loading case. Results of experiment can be simulated by the both formulas,

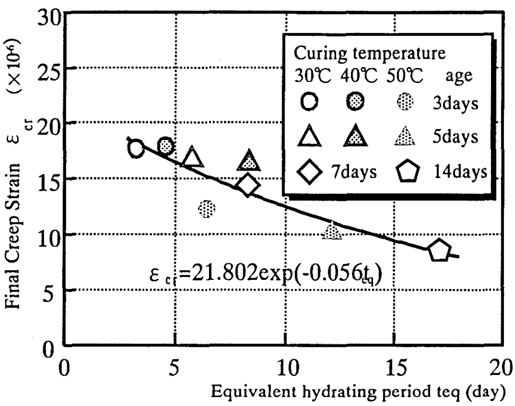

Fig.14 Effect of curing temperature and period

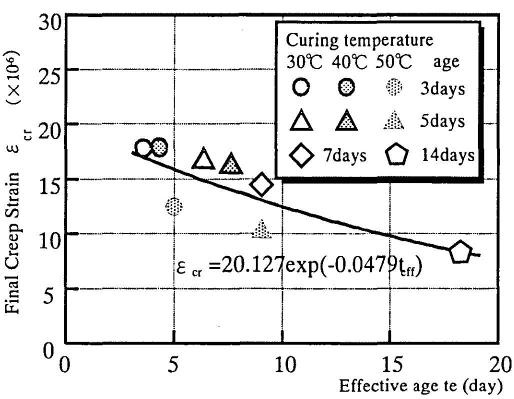

Fig.15 Effect of effective age

however the equivalent hydration period is better than effective age, since the ratio of equivalent hydration period is 0.911, and the ratio of effective ages is 0.810. It has been noted that the equivalent hydration period can be applied for assessment of temperature effect on curing [18], so, that the effect of high curing temperature and effect of extension of curing period are similar mechanism upon tensile creep generation. The effect of loading age and curing temperature on final creep strain can be described by the formula in **Fig.**10 and the equivalent hydration formula given as formula (4).

$$\varepsilon(t_{eq}) = 1.55\, t_{eq} - 13.07\sqrt{t_{eq}} + 35.42 \qquad (4)$$

c) Effect of loading temperature

The relationship between creep strain and loading period with S/S=40% and fixed curing conditions was obtained. The parameters in this test was loading temperature, which was set from 30℃ to 50℃.
The results are shown in **Figs.**16 and 17. It is noteworthy that creep strain increases with rising loading temperature. The effect of loading temperature with fixed curing temperature can be elucidated by Arrenius's theory, if concrete creep is assessed by rehology theory and accelerated by reducing the viscosity of the pore water of cement paste [19]. Formula for predicting creep strain is now derived based on Arrenius' theory by calculating the activation energy and taking the effects of both temperature and loading period into account. Arrenius' formula is described as follows.

$$k = \exp\left[\frac{\Delta U}{R}(273 + T)\right] \qquad (5)$$

k : Velocity of creep strain
ΔU : Difference of activation energy by temperature
R : Gas constant(8.315 J/mol/deg K)

Creep strain can be obtained by integrating formula (5) by time, as follows:

$$\varepsilon_{cr}(t_{cr}) = F\left(\int k\, dt\right)$$

$$= F\left\{\exp\left[\frac{-\Delta U}{R}(273 + T)\right]\right\} \qquad (6)$$

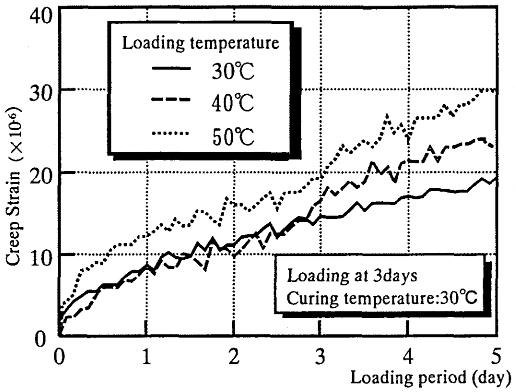

Fig.16 Effect of loading temperature

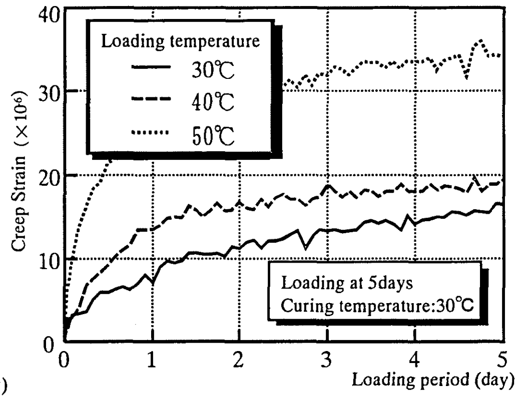

Fig.17 Effect of loading temperature

The standard temperature is 30℃ in this experiment, and the formula can be written as follows :

$$t_{eq} = \Sigma\{ \exp [\frac{-\triangle U}{R} (\frac{1}{271+30} - \frac{1}{271+T})\}\triangle t \tag{7}$$

This formula is similar to formula (1), which defines the equivalent hydration period, and formula (2) means that the standard temperature is 30℃ and $\triangle U/R$ is 4000 in formula (6). The value of $\triangle U/R$, by which the effect of loading temperature and loading period can be assessed simultaneously in a formula, was defined by simulating the results of tensile creep tests at several loading temperatures. That is, the activation energy of tensile creep was investigated at loading temperatures from 30℃ to 50℃, and modified equivalent hydration period was proposed upon tensile creep. This formula can take simultaneously effects of loading temperature and loading period into account. The relationships between two equivalent hydration periods and creep strains are shown in **Figs**.18 ~21; these were calculated by making $\triangle U/R$ in formula (6) 4,000 to 10,000. The best simulated value is 10,000 in the case of loading at 5 days and is 4,000 in the case of 3 days according to calculation in which $\triangle U/R$ is changed from 4000 to 15000. However, a certain value of $\triangle U/R$ which could give well fittings for every result of experiments was not found.

The equivalent hydration period as defined by Z.P.Bazant can be applied in the case of loading at 3 days, and a $\triangle U/R$ value 10,000 is required in the case of loading at 5 days. This means that the activation energy at 3 days is 33.5 kJ/mol, and that the value at 5 days is 83.7 kJ/mol. The activation energy derived from compressive creep tests by F.H. Wittmann was 20.9 kJ/mol [20], and the value achieved in this study is bigger than that. According to a study by the authors, compressive creep strain can be assessed from effective age [1]; however, the effect of temperature in the tensile creep test was more significant than that of compressive creep.

Consequently, it is thought that the mechanism of temperature dependence of tensile creep is different from that in compressive creep. Regarding the rise in activation energy corresponding to an increment in loading age, this means that the effect of pore water seepage is small and the defect zone -- including micro cracking -- dominates creep strain in the case of loading at 1 day, if the activation energy accelerate the creep strain at high temperatures. Quantitative definition of the activation energy on tensile creep is in future study. This will be the focus of several future experiments.

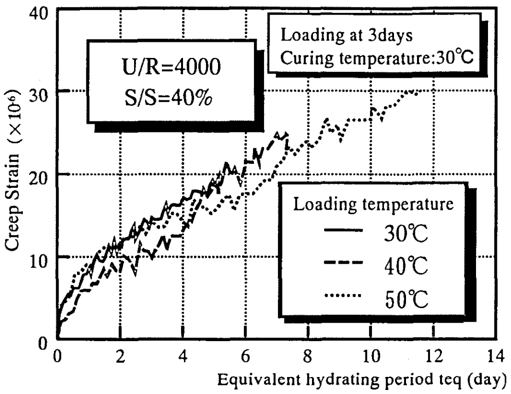

Fig.18 Effect of loading temperature

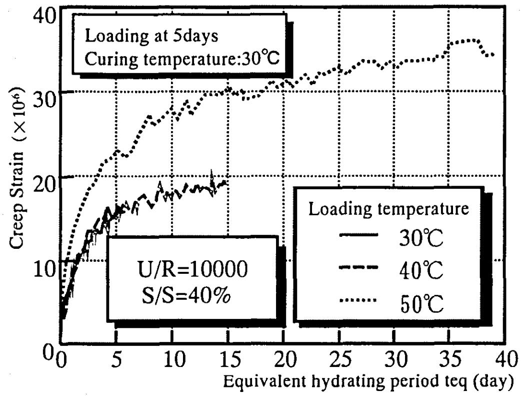

Fig.19 Effect of loading temperature

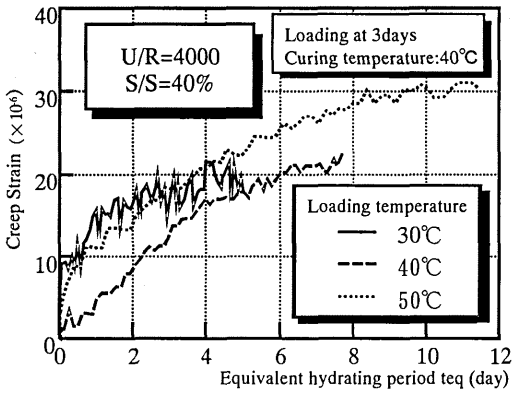

Fig.20 Effect of loading temperature

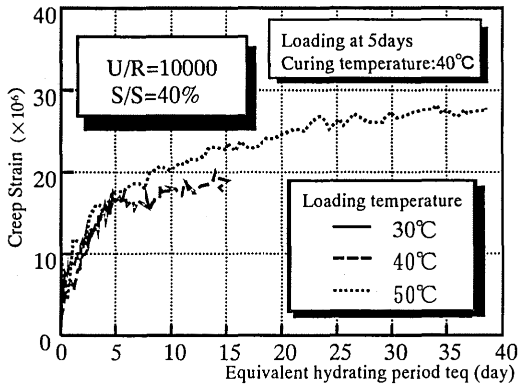

Fig.21 Effect of loading temperature

(6) Effect of creep strain on tensile failure

Creep strain is assumed to have no influence on steady tensile failure in thermal stress analysis, since it relaxes completely into constrained stress, such as thermal stress. Tensile failure tests were carried out by adding further stress after finishing the creep tests in order to investigate the effect of creep strain on tensile failure.

Strain capacity is defined as follows;.
(strain capacity) =
(strain at failure) – (creep strain) –
(strain of unloaded specimen, consisting of autogenous shrinkage etc.)

The stress-strength ratio, creep strain, and, strain capacity strain are shown in Table 4. The relation- ship between strain capacity and stress-strength ratio in the creep tests is shown in **Fig.** 22. Regarding the effect of creep strain on strain capacity, it should be noted that stress capacity of stress is lower S/S= 70%, although little effect is observed at less than 40%. It can be pointed out that tensile strain capacity should decreased by taking the effect of creep into account beyond S/S=70% from the results of this study. However, this effect hasn't been applied for prediction of cracking in thermal stress analysis. Specimens loaded at 1 day and 5 days with S/S = 80% failed in within 1 hour of adding all loads. Although it is considered that bending moment might be added by adjusting error of test apparatus, possibility of creep failure is not negligible.

Table. 4 Tensile strain capacity

Load -ing age	Loading Period	S/S	Elastic Strain	Creep strain	Failure strain	Tensile strain capacity	Shrinkage of unloading specimen
(day)	(day)	(%)	(μ)	(μ)	(μ)	(μ)	(μ)
1	5	40	18	35	123	106	-36
1	5	70	28	42	122	92	-55
1	5	20	7	26	106	112	-39
3	5	20	24	28	120	108	-10

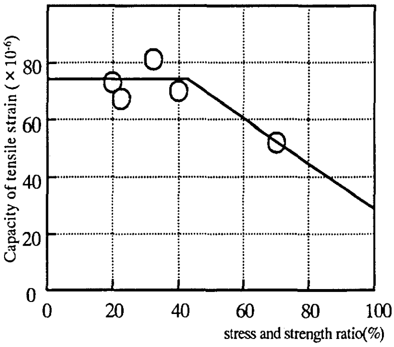

Fig.22 Tensile strain capacity

5. CREEP MODEL

(1) Basic creep model

A creep model that defines the relationship between creep strain and loading period is now presented. It is based on experiments with loading at 3 days, 30℃ and S/S=40% , and curing at 30℃. The creep model consists of a number of linearly connected Voight elements and a dash pot, as well as a model of compressive creep [1]. The tensile creep model is shown as follows ;

$$\varepsilon_{CR}(t)= 13.13 (1 - \exp (-1.02 t) + 32.09 (1-\exp (-0.18t)) + 0.05 t \qquad (8)$$

t : loading period at 30℃ curing temperature
$\varepsilon_{CR}(t)$: Creep strain

It has already been noted that the equivalent hydration period defined by Z.P.Bazant is applicable to tensile creep in the case of loading at 3 days and that a modified period larger than this is required in the case of loading at 5 days. A model for predicting thermal stress requires a relation that is modeled by same kind of hydration period, since calculation and consideration are simple. Consequently, since the few days following concreting are very important, a modified hydration period is adopted in order to take both temperature and period into account, although it might estimate larger than actual effects.

$$t'_{eq} = \Sigma \{ \exp [10000 (\frac{1}{271+T_0} - \frac{1}{271+T})\} \Delta t \qquad (9)$$

t'_{eq} : Modified equivalent hydration period

The basic creep model can be described as follow ;

$$\varepsilon_{CR}= 13.13 (1 - \exp (-1.02 t'_{eq}) + 32.09 (1-\exp (-0.18t'_{eq})) + 0.05 t'_{eq} \qquad (10)$$

(2) Effect of loading age

It was confirmed in this experimental study that the effect of curing temperature and loading age can be modeled with the equivalent hydration introduced by Z.P. Bazant. This equivalent hydration period is applied for the curing period and temperature effects in the basic model. Although the effect of loading age and curing temperature are defined by formula (3), a compensated formula was based on the results of loading at 3 days is described as follows;

$$F_L(t_{eq}) = 0.09 t_{eq} -0.75 \sqrt{t_{eq}} + 2.03 \qquad (11)$$

(3) Effect of stress-strength ratio

It has been noted that the effect of strength ratio on effects for tensile creep strain depends on loading age. Two compensated two formulas were defined for the case of loading at 1 day and other ages, since loading at 1 day can be considered an indepent case. The relationship between tensile creep strain and the stress-strength ratio can be described as in formula (11) based on **Fig.**8. Since the linear relationship between stress-strength ratio and final creep strain has been defined for S/S value of less than 20% by previous studies [20], a proportional formula is defined.

$$\left.\begin{array}{ll} \text{In the case of } S/S\cdot \leqq 20\% & \\ \quad \varepsilon_{cr}(S/S) = 1.47\ S/S & (t_{eq} \leqq 1) \\ \quad \varepsilon_{cr}(S/S) = 1.20\ S/S & (t_{eq} \geqq 1) \\ \text{In case of } S/S\cdot \geqq 20\% & \\ \quad \varepsilon_{cr}(S/S) = 25.08 \exp(0.01\ S/S) & (t_{eq} \leqq 1) \\ \quad \varepsilon_{cr}(S/S) = 1.28 \exp(0.06\ S/S) & (t_{eq} \geqq 1) \end{array}\right\} \quad (12)$$

A compensated formula is defined as follows based on S/S=40% ;.

$$\left.\begin{array}{ll} \text{In the case of } S/S \leqq 20\% & \\ \quad F_{S/S} = 0.50\ S/S & \\ \text{In the case of } S/S \geqq 20\% & \\ \quad F_{S/S} = 0.73 \exp(0.008 S/S) & (t_{eq} \leqq 1) \\ \quad F_{S/S} = 0.10 \exp(0.057 S/S) & (t_{eq} \geqq 1) \end{array}\right\} \quad (13)$$

(4) Proposed tensile creep formula based on experiments at early age

A formula defining tensile creep strain based on the creep experiments is dined as follows ;

$$\left.\begin{array}{l} \varepsilon_{cr}(t'_{eq}, t_{eq}, S/S) = F_L(t_{eq})\, F_{S/S}(S/S)\, [13.13(1-\exp(-1.02t'_{eq})) + \\ \qquad 32.09\,(1-\exp(-0.18t'_{eq})) + 0.05\, t'_{eq}] \\[2ex] t_{eq} = \Sigma\, \{\exp[4000\,(\dfrac{1}{273+30} + \dfrac{1}{273+T})]\}\triangle t \\[2ex] t_{eq}' = \Sigma\, \{\exp[10000(\dfrac{1}{273+30} + \dfrac{1}{273+T})]\}\triangle t \end{array}\right\} \quad (14)$$

Results in which calculated values using the formula are compared to experimental results at S/S=50%, 30℃ of curing temperature, and 30℃ loading temperature are shown in **Fig.**23. The values corresponding to a loading period of 20 days are quite well matched. It can thus be said out that the basic creep formula and super - positioning principle are suitable for the prediction of thermal stress for 20 days of loading.

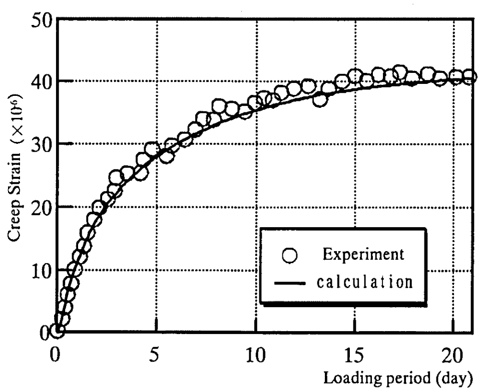

Fig.23 Fitting by basic creep formula

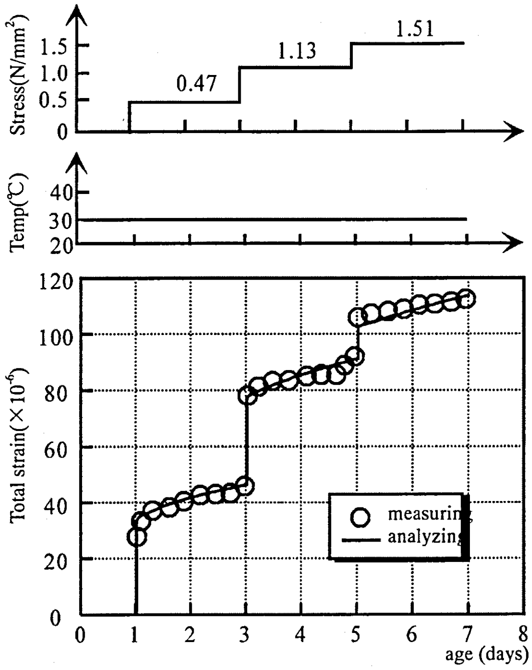

Fig.24 Comparison of measured value and analysis

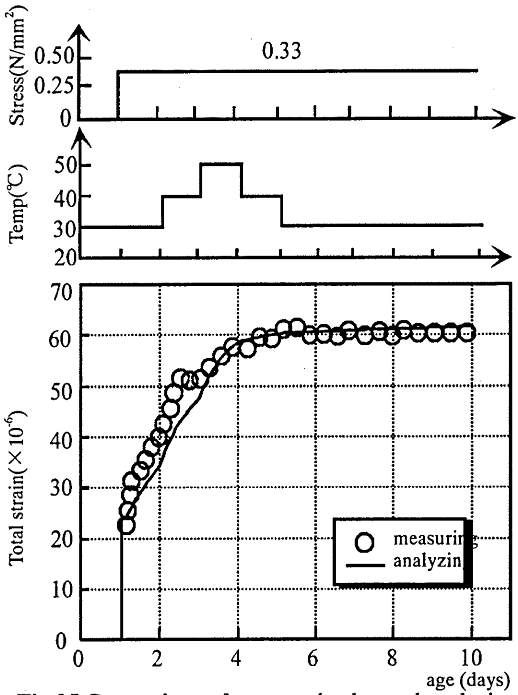

Fig.25 Comparison of measured value and analysis

6. APPLICATION TO VARYING STRESS SUCH AS THERMAL STRESS

(1) Application to simplified increment of tensile stress

A creep test in which the stress-strength ratio was fixed at 60%, the curing and loading temperatures were 30℃, and loading was 1 day was carried out. The value of loaded tensile stress gradually increased with rising strength. Results of this tensile creep test is shown in **Fig**.24. The measured creep strain was compared to calculated creep strain obtained with the proposed creep formula using the and super-positioning principle at each step [1]. Although the effect of stress-strength ratio can not be accurately

simulated by super - positioning at each step in this way, the calculation and test results are well similar at S/S=60%. Super - positioning principle can be practically applied for actual prediction, although non linearity on stress-strength ratio is not taken into account. Authors also pointed out that super-positioning can be applied to compressive [1]. Applicability to bigger stresses and strengths is difficult to assess at present.

(2) Application to varying temperature

Creep tests, with loading at one day and S/S=40% and the loading temperature was changed, were carried out. The results of the tests and the calculated values obtained by proposed creep formula and super - positioning principle are shown in **Fig**.25. Although the creep strain increases with rising corresponding to increment of temperature, the calculation closely simulates the actual results. This creep formula is thus able to simulate creep strain under varying temperatures.

7. CONCLUSION

The results obtained in this study are described as follows.

1) The effects of stress-strength ratio on creep strain when loading takes place at 3 to 7 days of loading age are significant. No linear relationship was observed at low stress-strength ratios such as 20% ~40%. Creep strain significantly increased beyond S/S=60 %.
2) The creep strain with loading at 1 day is larger than that when loading takes place at 3 days ~ 7 days for low stress-strength ratios such as 20% ~40%. Furthers, the effects of stress-strength ratio with loading at 1 day are less significant than with loading at 3 ~7 days. It is considered that the creep strain with loading at 1 day is larger than in other cases, since micro cracking easily occurs due to weakness of the cement hydrate.
3) Tensile creep strain decreases at early age with loading age. However, this effect of loading age is smaller than that of stress-strength ratio.
4) Effects of loading age and curing temperature can be assessed together by considering an equivalent hydration period.
5) Since the effect of loading temperature in tensile creep strain is more significant than that in compressive creep strain, it can not be assessed by adopting equivalent hydration period. It is proposed that the effects of both loading temperature and period can be assessed together by using a modified equivalent hydration period obtained as 83.7 kJ/mol of activation energy.
6) Tensile creep strain induces little effect on tensile failure for S/S=20 ~ 40%. Certain effects can be observed in tensile failures at more than S/S=70 %, such as decreasing strain capacity to failure at high stress-strength ratio.
7) A tensile creep model consisting of 5 Voigt model elements is proposed to which can simulate varying stress and temperature.

Further studies will continue so as to investigate activation energy, the tensile creep mechanism, and creep failure.

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