Effect of Step-wise Change of Stress and Temperature on Primary Creep of Concrete

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1 INTRODUCTION

The success of analyzing the behavior of concrete structures at elevated temperature greatly depends on how accurately certain mechanical properties, especially the stress-strain curve, creep and thermal expansion can be determined within a wide temperature range.

The importance of creep in the design of reinforced and prestressed concrete structures has been more recognized with the advent of use of concrete at elevated temperature.

The almost of our knowledge for the creep characteristic in solid is obtained from creep test under constant load and temperature. In the previous papers[1,2], the stress-strain relationship at elevated temperature and creep behavior under constant load and temperature have been investigated. The maximum stress, strain at maximum stress and secant modulus of elasticity vary with increasing temperature. The creep strain is affected by stress, time and temperature. The creep strain of concrete in general increases with time under constant load and temperature. However, the internal stress and temperature distributions in a reinforced concrete structure under varying temperature vary with time. Therefore, the creep law which can predict the creep behavior under varying stress and temperature by using the experimental results of creep strain under constant stress and temperature is indispensable for analyzing the behavior of reinforced concrete structures under varying temperature. Accordingly, the main purpose of this study is to make clear the primary creep behavior under varying stress and temperature.

2 SPECIMENS

Step-wise change of stress: Concrete cylinders 5ϕ x10 cm aged for about 10 years were used: w/c=65 and 45%, σ_u=325 and 524kg/cm^2.
Step-wise change of temperature: Concrete cylinders 5ϕ x10 cm aged for about 10 months were used: w/c=66, σ_u=260kg/cm^2.

3 TESTING PROCEDURE

Tests were carried out with the same apparatus and procedure as those of Refs 1 and 2.
Step-wise change of stress: Each specimen was tested at constant temperature

which covered the temperature range from 100 to 600℃ at 50~100℃ increments and under step-wise varying stresses for 3~4 hours. The applied step-wise stresses at each temperature were 2 to 4 steps at 25~80 kg/cm^2 increments.

Step-wise change of temperature: Each specimen was tested under a constant stress which covered the 50 to 150 kg/cm^2 stress range at the step of 50 kg/cm^2 and under step-wise varying temperatures for approximately 3 or 5 hours. The specimen is subjected to a constant heating rate (1.4℃/min.), when the temperature is raised from a constant temperature T_1 to a higher value T_2. The applied step-wise temperatures at each stress level were 2 to 3 steps under the 450 to 550℃ temperature range at 50℃ increments.

Also, the creep tests under constant stresses and temperatures were performed.

4 RESULTS AND DISCUSSION

Step-wise change of stress: The typical total strain-time curves for concrete under variable stresses are shown in Fig.1. In these figures, the marks "←" show the start of creep test and the vertical lines show the elasto-plastic strains caused during the loading. The creep curve obtained under constant loads at elevated temperature are shown for reference in Fig.2. The examples of stress-strain curves obtained together with creep curves are shown in Fig.3. In these figures, the horizontal straight lines show the creep strains and curves following them show the stress-strain curves obtained at the times changing the stress levels and after the finish of creep tests. The two-dashed lines are assumed by the curves which pass through the start points of creep tests and maximum stress point using Eq.(1) in reference 1).

$$\sigma/\sigma_{max} = \exp(1 - \varepsilon/\varepsilon_{max}) \cdot \varepsilon/\varepsilon_{max} \quad \cdots\cdots\cdots\cdots (1)$$

where σ, ε, σ_{max} and ε_{max} are stress,strain, maximum stress and maximum stress, respectively. Fig.4 show the representative creep-time curves under step-wise change of stress.

The effect of creep on reinforced concrete structures at elevated temperature is very important. The creep strain of concrete becomes great under very high stress or very high temperature.

In the case of prestressed concrete pressure vessels for nuclear power plants, stresses in concrete vary with time, and the problem becomes to find out the creep law for predicting the creep behavior under varying stress from the test results under constant stress.

Step-wise change of temperature: The typical creep and stress-strain curves obtained on the recorder of the testing machine are shown with solid line in Fig.5. In this figure, the creep curve do not show true value, because these involves the transient expansions and contractions of specimens and the extensometer caused by the variation of temperature. To eliminate the apparent strain by temperature fluctuation, the tests in which applied loads for specimens were zero and only the temperatures were changed step-wise were carried out beforehand (see Fig.6). The true creep strain under the step-wise change of temperatures can be obtained by eliminating the strain under zero stress and step-wise changing temperatures and the variation of elastic strain under step-wise changing temperatures from the strain under constant stress not equal to zero and step-wise temperatures, in consideration of the variation of thermal expansion strain and elastic strain caused by the temperature fluctuation.

The curves eliminated the apparent strain due to the variation of temperature under zero load are shown with dashed curves ("Revised Curve") in Fig.5. Further, the curves obtained above, are corrected by the variation of elastic strain at the applied stress level and are shown with "Revised

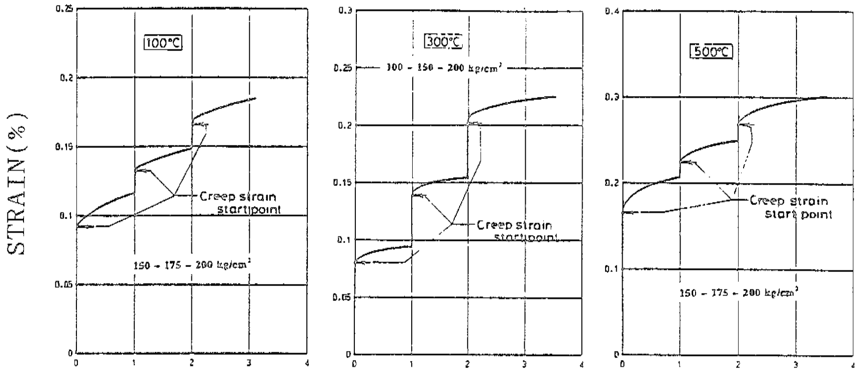

Fig.1 Total strain-time curves (W/C=65%)

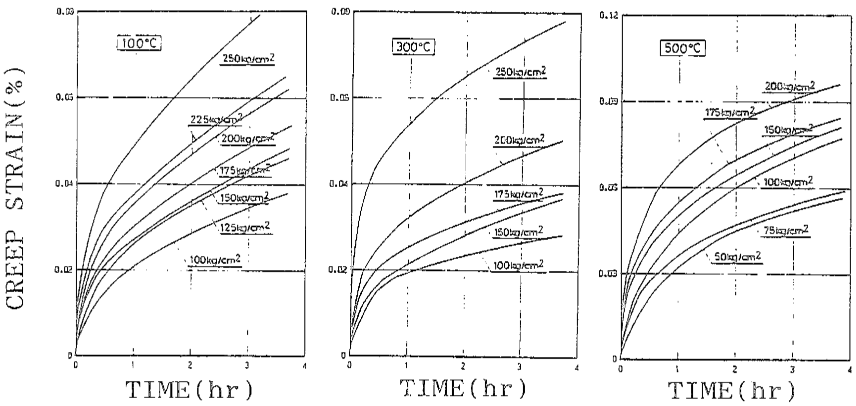

Fig.2 Creep curves under constant loads(W/C=65%)

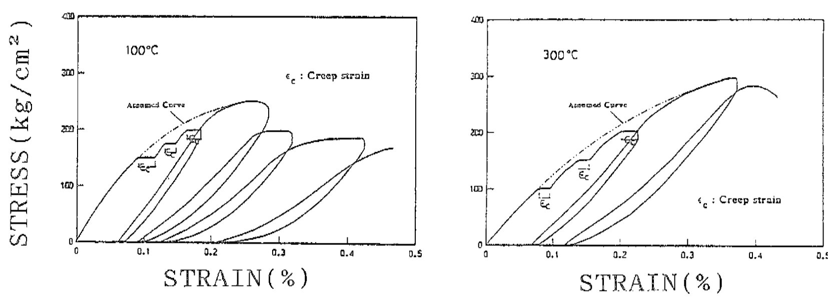

Fig.3 Stress-strain curves (W/C=65%)

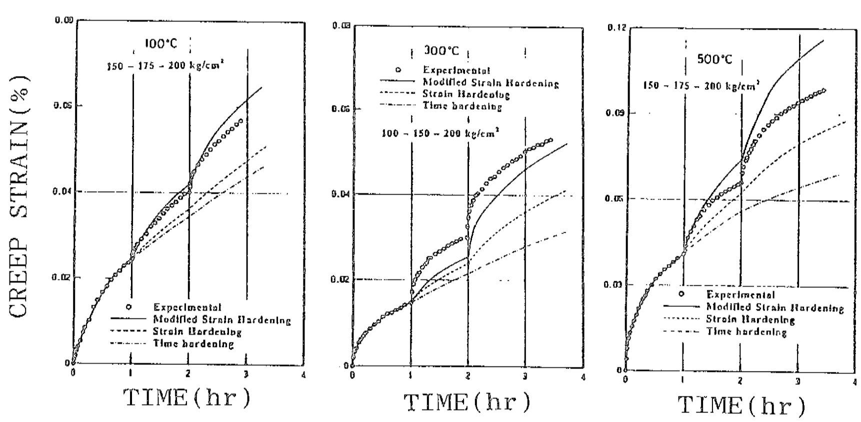

Fig.4 Experimental and calculated creep(W/C=65%)

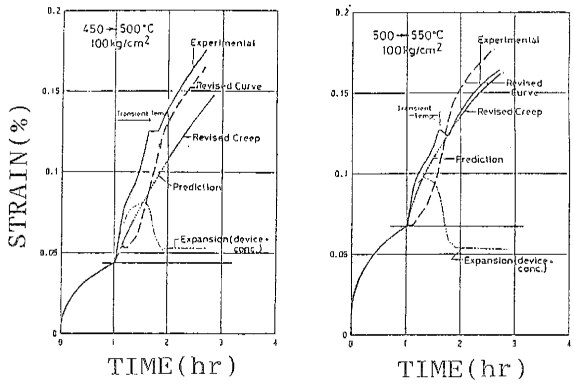

Fig.5 Typical creep curves obtained on recorder

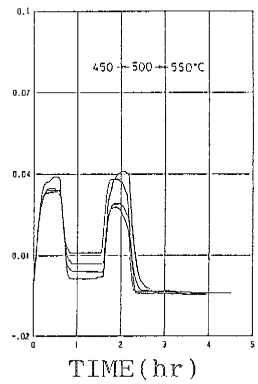

Fig.6 Apparent strain under zero load

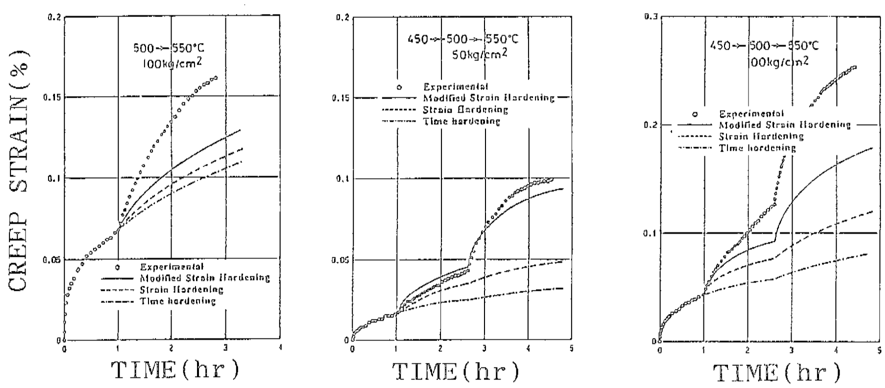

Fig.7 Experimental and calculated creep

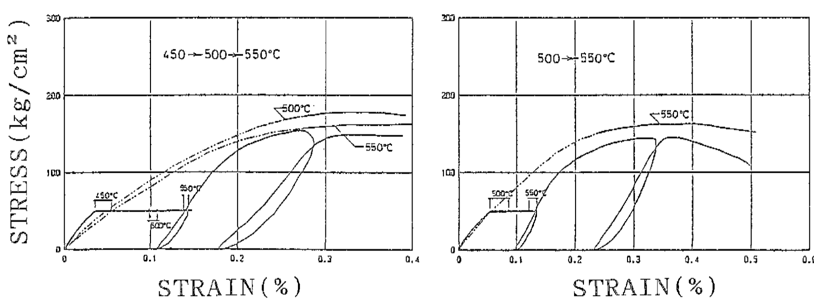

Fig.8 Stress-strain curves

Creep"in Fig.5.

The creep curves under step-wise varying temperatures are plotted with the marks, "○" and "◍", in Fig.7. In these figures, the mark,"○", shows the true creep strain and mark, "◍", shows the predicted creep strain under the transient temperature range. The stress-strain curves obtained togther with creep curves are shown in Fig.8.

5 MODIFIED STRAIN-HARDENING LAW

Step-wise change of stress: Although plastic strain is defined as time independent, it is a function of time in the strict sence. In the creep test, it is difficult to distinguish clearly between plastic and creep strain, especially for a short while after the loading. Therefore, it seems reasonable to take plastic strain into consideration in addition to creep strain, when the strain-hardening law is applied. The strain-hardening law in which plastic strain is taken into account as the same kind of strain as creep is called a modified strain-hardening law in this paper.

This law will be understood immediately from Fig.9. If, for instance, the stress is raised from a constant stress σ_1 to a higher value σ_2 after a certain time period t_1 (see Fig.9-1), the creep strain caused during the time period t_1 is ε_b and at the time t_1 the value of stress and strain change from those of B to C in Fig.9-1. After that, the creep strain follows the curve CD and after the lapse of time t_1+t_2, the total creep strain becomes $\varepsilon_b+\varepsilon_{cd}$. In this case, the creep curve is O_1BCD.

In Fig.7, the results obtained by the modified strain-hardening law using experimental results obtained with constant stresses and temperatures are shown with solid curves. It is apparently shown that the modified strain-hardening law gives considerably a good approximation in comparison with the time- or strain-hardening law.

Step-wise change of temperature: Now, the modified strain-hardening law is applied to the case involving a nonsteady state temperature history under constant stress. In this law, it is assumed as a matter of course that if the temperature is change from a constant temperature (T_1 or T_2) to another one (T_2 or T_1), the stress-strain curve changes as shown in Fig.10.

This law will be understood immediately from Fig.10. If, for instance, the temperature is raised from a constant temperature T_1 to a higher value T_2 in a moment after a certain time period t_1 in which the creep strain $\overline{AB}(=\varepsilon_{c1})$ has been caused, at the time t_1 the value of elastic and plastic strains change. Therfore, the value of strain (elasto-plastic-creep strain) changes from that of B to D in Fig.10 with the strain increment equal to the difference of elastic strains $\Delta\varepsilon$ $(=\overline{AC'})$, according to the assumption that the sum of the plastic and creep strain is constant. In this case, the value of creep strain changes from $\overline{AB}(=\varepsilon_{c1})$ to $\overline{CD}(=\varepsilon_{c2})$. After that, the creep strain follows the curve DE(Fig.10). Also, in the case where the temperature is descended, it is assumed that the stress-strain relationship does not change and the creep strain $\overline{CD}(=\varepsilon_{c2})$ is constant, because the concrete subjecting to higher temperatures is not expected to cause the recovery of mechanical properties as shown in Fig.11. In Fig.7, the results obtained by the modified strain-hardening law using experimental results obtained under

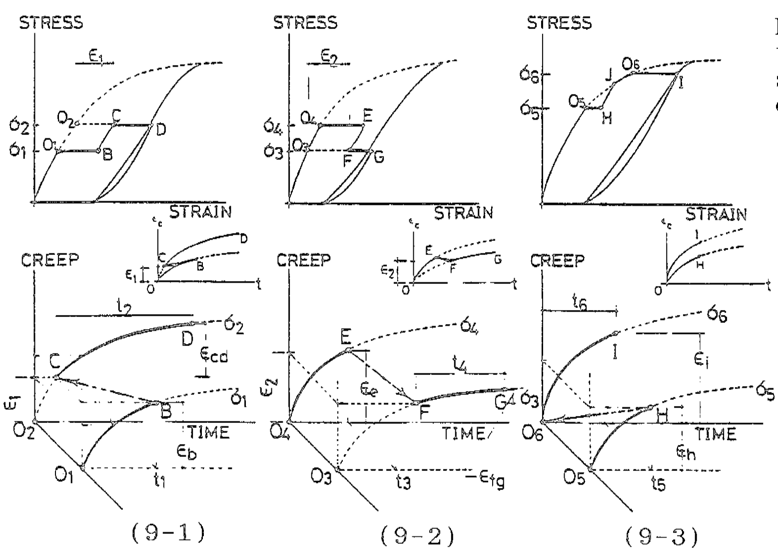

Fig.9 Illustration of modified strain-hardening creep law

constant stresses and temperatures are shown with solid curves.
It is shown that the modified strain-hardening law gives relatively a good approximation in comparison with the time- or strain-hardening law.

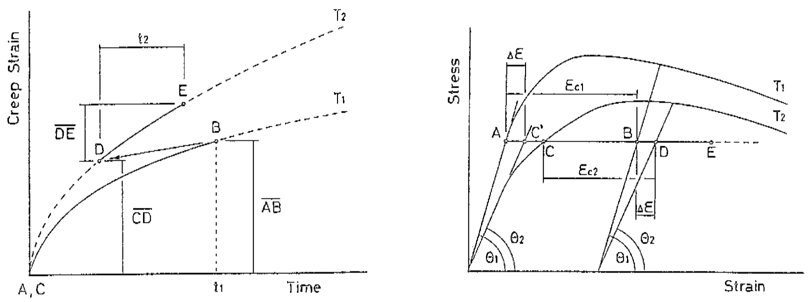

Fig.10 Stress-strain relationship accompanied with creep strain under step-wise varying temperatures and constant stress

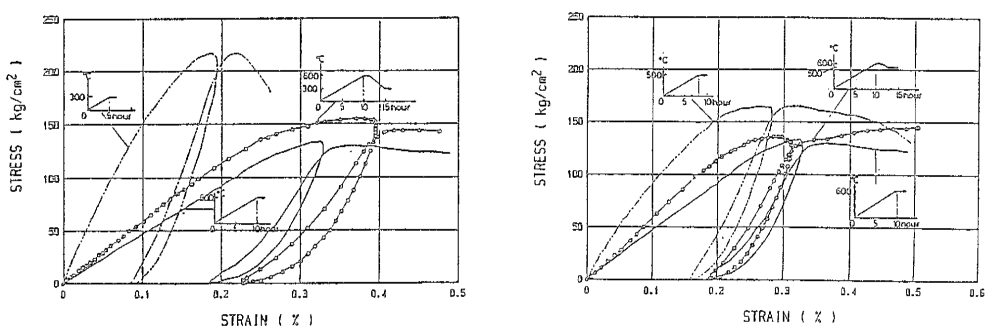

Fig.11 Stress-strain curves at variable temperatures

6 CONCLUSION

The following general conclusion are drawn from the results of this investigation. Using the modified strain-hardening law, the primary creep behavior of concrete under varying stress and temperature can be estimated with more certainty than the time- or strain-hardening law which has been widely used. The creep tests under step-wise change of stress and temperature show that it is important to consider simultaneously not only creep strain but also elasto-plastic strain for analyzing the creep deformation of structures under variable stresses and temperatures.

REFERENCES

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