CREEP BEHAVIOR OF TUFFACEOUS ROCK AT HIGH TEMPERATURE OBSERVED IN UNCONFINED COMPRESSION TEST

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ABSTRACT

Geological disposal in soft rocks is expected as one of the most practicable methods for isolation of high-level radioactive wastes. Since the country rock around the deep tunnels tends to be heated for a long term due to continuous collapse of nuclides, creep behavior of the soft rocks of impermeable nature under high temperature should be studied. Under different temperatures from 24°C to 95°C, a series of unconfinement compression tests was conducted on a tuffaceous rock, Ohya stone, at creep stress ratios ranging from 0.6 to 1.0. The results show that the creep behavior is accelerated by high temperatures over 60°C. That is, for higher temperatures, the time to failure is decreased, while the minimum strain rate is increased. A creep model is then presented, in which attention is paid to the change in strain rate with time. Unique relationships between the minimum strain rate and various creep parameters are used, that appear to be dependent on neither creep stress ratio nor temperature. According to the proposed model, the creep failure will not take place if the creep stress ratio is lower than 0.44.

Key words: constitutive model, creep, geological disposal, soft rock, strain rate, temperature, unconfined compression test (IGC:F6/G2)

INTRODUCTION

Geological disposal is seen as one of the most practicable methods for isolation of high-level radioactive wastes. Sedimentary soft rocks, especially mudstones, are expected as one of the prime candidate as country rock for this facility (NUMO, 2003). Because they are least jointed thereby impermeable sufficiently to prevent such hazardous wastes from leakage.

The country rock around the disposal tunnels tends to be heated for a long term due to continuous collapse of nuclides for over tens of thousands of years. The temperature of the surrounding rock mass close to the heat source is expected to rise as high as 100°C (JNCDI, 2000). Therefore, long-term behavior, i.e. creep, of soft rocks in high temperatures should be studied.

Four reports were found in the literatures on uniaxial creep behavior of soft rocks under high temperatures. Yamabe et al. (2001) revealed that creep behavior of a tuffaceous rock under temperatures from −10°C to 55°C was accelerated for higher temperatures. Similar findings were reported with a diatomaceous mudstone under 20–90°C (Jo et al., 2005) and with a sandstone under 1–80°C (Kodama et al., 2005). However, Kato et al. (2004) reported that creep behavior of a mudstone was independent of temperatures from 20°C to 60°C. As these reports contradict each other, more experimental studies are needed to elucidate the influence of temperatures on creep behavior of soft rocks. Attention should be paid to the rock type, and to high temperatures close to 100°C for the geological disposal of high-level radioactive wastes.

Effects of temperature on creep behavior under confining pressures were also investigated in triaxial tests by Hettema et al. (1991) and Thimus and De Bruyn (1998). Their results demonstrated marked influence of temperature, but only limited test results were reported.

In this study, under different temperatures from 24°C to 95°C, a series of unconfinement compression tests was conducted on a tuffaceous rock, Ohya stone. Creep stress ratios were varied from 0.6 to 1.0. On the basis of the experimental data, Kato et al. (2004)'s creep model was improved to take into account the influence of temperature.

METHOD OF CREEP TEST

Test Apparatus

Figure 1 shows the unconfined compression test apparatus specifically designed for creep tests under high temperatures. The application of sustained axial load is made by leveraged dead weights to forestall power failures. The maximum load, 50 kN, can allow application of axial stress, 25 MPa, on a specimen of diameter 50

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The manuscript for this paper was received for review on July 4, 2005; approved on July 26, 2006.

Written discussions on this paper should be submitted before September 1, 2007 to the Japanese Geotechnical Society, 4-38-2, Sengoku, Bunkyo-ku, Tokyo 112-0011, Japan. Upon request the closing date may be extended one month.
mm.

The specimen placed in the insulated cell is submerged in the water circulated by a pump. The temperature of the water is controlled in a thermostatic bath equipped with heat source.

Measurements are made for temperature by a thermocouple, axial load by a load cell, and axial displacement by a LVDT, respectively. Moreover, both axial and lateral strains are measured by strain gages pasted on lateral surface of a specimen at opposite diagonal positions. Note that external measurement by the LVDT may suffer from bedding errors (Matsumoto et al., 1999). Whereas local measurement by strain gages is believed to be more representative of specimen’s behavior, and is used for further analysis.

Specimen

Rhyolitic welded tuff of Miocene deposit, denoted as Ohya stone or green tuff, was used as the test material. Twenty-five cylindrical specimens of diameter $d = 50$ mm and height $h = 100$ mm were drilled from dry cubic blocks of about 300 mm. For saturation, they were kept in the water and deaerated for two weeks.

The size, the weight, and the ultra-sonic wave velocities were measured of all the specimens. As shown in Fig. 2, the total unit weight $\gamma = 18.51$ (mean value) $\pm 0.26$ (standard deviation) kN/m², the shear wave velocity $V_s = 1082 \pm 47$ m/s and the longitudinal wave velocity $V_p = 2474 \pm 99$ m/s were found within the ranges of previous studies on Ohya stone (Kuwabara, 1984; Nakajima et al., 2000; Kurumura et al., 2003). Consistent data with small variations ensured that these specimens were practically identical to each other.

Eight unconfined compression tests (JIS A 1216–1998) were conducted under temperatures $T = 24$°C, 80°C and 95°C (Miho, 2005). As shown in Fig. 3, the values of unconfined compression strengths were $q_u = 5.74 \pm 0.43$ MPa at ordinary temperature, 24°C, and decrease linearly with increasing temperature. As reference strengths, the values of $q_u$ (MPa) can be estimated as a function of $T$ (°C) obtained by linear regression.

$$q_u = -0.0149T + 6.10$$ (1)

The creep stress ratio, $q_{\text{creep}}/q_u$, is defined for the respective values of $T$, where $q_{\text{creep}}$ is the axial stress during creep.

Loading and Measurement

After the specimen placement in the insulated cell, the temperature of the cell water was raised gradually, 0.5°C/min., to the intended value. The specimen was then left for at least thirty minutes before application of axial load. This is to allow the temperature of the specimen to become the same as that of the cell water, which is controlled with the maximum variation of $\pm 0.5$°C.

To avoid impact or dynamic effect on the specimen, the axial load was raised slowly, 0.23–0.45 MPa/s, to attain the intended creep stress, $q_{\text{creep}}$, in 10–17 seconds. From the start of load application, measurement were made every 0.5 second for 30 minutes, and then the interval was set 1 minute after that.

Data Analysis

The creep time, $t_\gamma$, is defined as the elapsed time since the axial stress reached the intended creep stress.

Although the axial load was kept constant during creep, the axial stress was slightly decreased as the cross-section of the specimen was increased gradually with creep deformation. So, the creep stress, $q_{\text{creep}}$, is determined as the average axial stress for $0 < t_\gamma < t_\alpha$, where $t_\alpha$ is
the time to creep failure. The values of \( t_{cf} \) can be determined with least variations, as the creep failures take place abruptly; thereby defined by an arbitral value of axial strain, \( \varepsilon_a = 2\% \), in this study.

**Test Cases**

Seventeen tests were carried out as shown in Table 1. To study the influence of creep stress ratio, \( q_{creep}/q_u \), and temperature, \( T \), on creep behavior, the range of \( q_{creep}/q_u \) was set from 0.6 to 1.0 and that of \( T \) was set from 24°C to 95°C, respectively. Three specimens were failed before the intended creep stress was loaded, thereby \( \varepsilon_{u0} > 2\% \). Furthermore, three tests were stopped before creep failure, as the primary creep appeared to continue intolerably long time.

**CREEP MODEL AND CREEP PARAMETERS**

In general, creep behavior of rocks is categorized into three stages taking into account the change of strain rates, \( \dot{\varepsilon}_a \), as shown in Fig. 4(a). In the primary creep, \( \dot{\varepsilon}_a \) decreases with time asymptotically to a certain value. In the secondary creep, \( \dot{\varepsilon}_a \) becomes constant; thus the minimum strain rate, \( \dot{\varepsilon}_{a,min} \). In the tertiary creep, \( \dot{\varepsilon}_a \) increases acceleratingly with time leading to creep failure.

Kato et al. (2004) proposed a creep model based on this three stages concept. As shown in Fig. 4(b), the double logarithmic relationship between strain rate, \( \dot{\varepsilon}_a \), and creep time, \( t_c \), in the primary creep is modeled by a linear expression. The strain rate in the secondary creep is then equated to the minimum strain rate, \( \dot{\varepsilon}_{a,min} \). As shown in Fig. 4(c), in the tertiary creep, the double logarithmic relationship between \( \dot{\varepsilon}_a \) and time left before failure, \( t_{cf} - t_c \), is again modeled by a linear expression. The slopes of the lines in Figs. 4(b) and 4(c) for the primary creep and the tertiary creep are defined as \( m_1 \) and \( m_3 \), respectively.

The transition time from the primary creep to the secondary creep, \( t_{c1} \), is determined from the intersection of the respective regression lines in Fig. 4(b). The transition time from the secondary creep to the tertiary creep, \( t_{c2} \), is also determined from the intersection of the respective regression lines in Fig. 4(c).

As above, the strain rates, \( \dot{\varepsilon}_a \), in each creep stage can be expressed by the following equations;

**Primary creep** (\( 0 < t_c \leq t_{c1} \))

\[
\log \dot{\varepsilon}_a = m_1 \log \left( \frac{t_c}{t_{c1}} \right) + \log \dot{\varepsilon}_{a1} \tag{2}
\]

**Secondary creep** (\( t_{c1} < t_c \leq t_{c2} \))

\[
\dot{\varepsilon}_a = \dot{\varepsilon}_{a,min} \tag{3}
\]

**Tertiary creep** (\( t_{c2} < t_c \leq t_{cf} \))

\[
\log \dot{\varepsilon}_a = m_3 \log \left( \frac{t_{cf} - t_c}{t_{cf} - t_{c2}} \right) + \log \dot{\varepsilon}_{a,min} \tag{4}
\]

where \( \dot{\varepsilon}_{a1} \) is the reference axial strain rate at the reference time, \( t_{c1} \).

By integration of these strain rates for respective creep stages, \( \dot{\varepsilon}_a \), the following equations can be obtained to calculate the change of axial strains, \( \varepsilon_a \), with creep time, \( t_c \), as shown in Fig. 4(d):
Fig. 4. Creep model and creep parameter

Primary creep (0 < t_c \leq t_{c1})
\[ \dot{e}_a = \frac{\dot{e}_{a0} t_{c1}}{(m_1 + 1)} \left( \frac{t_{c1}}{t_c} \right)^{m_1+1} + \dot{e}_{a0} \]  
(5)

Secondary creep (t_{c1} < t_c \leq t_{c2})
\[ \dot{e}_a = \dot{e}_{a,\min}(t_c - t_{c1}) + \dot{e}_{a1} \]  
(6)

Tertiary creep (t_{c2} < t_c \leq t_{cf})
\[ \dot{e}_a = \dot{e}_{a,\min}(t_c - t_{c2}) \left\{ 1 - \left( \frac{t_{c1}}{t_{c1} - t_{c2}} \right)^{m_3+1} \right\} + \dot{e}_{a2} \]  
(7)

where \( \dot{e}_{a0} \) is the initial axial strain at \( t_c = 0 \) minute, and \( \dot{e}_{a1} \) and \( \dot{e}_{a2} \) are the axial strain at \( t_c = t_{c1} \) and \( t_c = t_{c2} \), respectively.

On the whole, the proposed model is described with a total of eight creep parameters, i.e. \( m_1, m_3, t_{c1}, t_{c2}, \dot{e}_{a0}, \dot{e}_{a1}, \dot{e}_{a,\min} \) and \( t_{cf} \), which can be easily determined by the above-mentioned procedure from the test results. The transition times, \( t_{c1} \) and \( t_{c2} \), can be replaced by the relative transition times, \( t_{c1}/t_{c1} \) and \( t_{c2}/t_{c2} \).

**TEST RESULTS**

Figures 5(a) to 5(d) compare typical test results obtained for creep stress ratio between 0.84 and 0.91 under different temperatures. The following features are drawn.

1) Change of strain rate with creep time is typically characterized by three creep stages, i.e. primary, secondary and tertiary creeps, as shown in Fig. 4.

2) As shown in Figs. 5(b) and 5(c), the double logarithmic relationships between \( \dot{e}_a \) and \( t_c \) in the primary creep and between \( \dot{e}_a \) and \( t_{cf} - t_c \) in the tertiary creep appear to be expressed by linear expressions.

3) Creep behavior is accelerated for higher temperatures, especially for over 60°C (Shibata et al., 2004).

**INFLUENCE OF TEMPERATURE ON RELATIONSHIPS BETWEEN CREEP PARAMETERS AND CREEP STRESS RATIO**

Figures 6 to 11 summarize the relationships between some creep parameters and the creep stress ratios, \( q_{\text{creep}}/q_u \), obtained under different temperatures, \( T \).

Figure 6 shows the relationship between \( m_1, m_3 \) and \( q_{\text{creep}}/q_u \). \( m_1 \) represents the deceleration of strain rate in the primary creep stage, and \( m_3 \) represents the acceleration of strain rate in the tertiary creep stage. The values of \( m_1 \) seem to increase from \(-0.9\) to \(-0.6\) with the values of \( q_{\text{creep}}/q_u \) from \(0.6\) to \(1.0\), but independent of \( T \). Although the values of \( m_3 \) range similar values, they are dependent
Fig. 5(a). Relationship between $\dot{\epsilon}_a$ and $t_c$ for $q_{\text{creep}}/q_u = 0.84–0.91$

Fig. 5(b). Relationship between $\dot{\epsilon}_a$ and $t_c$ for $q_{\text{creep}}/q_u = 0.84–0.91$

Fig. 5(c). Relationship between $\dot{\epsilon}_a$ and $(t_{cf} - t_c)$ for $q_{\text{creep}}/q_u = 0.84–0.91$

Fig. 5(d). Relationship between $\dot{\epsilon}_a$ and $t_c$ for $q_{\text{creep}}/q_u = 0.84–0.91$

Figure 6. Relationship between $m_1$, $m_3$ and $q_{\text{creep}}/q_u$

Figure 7. Relationship between $t_{cf}$ and $q_{\text{creep}}/q_u$

Figure 8 shows the relationship between $t_{c1}/t_{cf}$, $t_{c2}/t_{cf}$ and $q_{\text{creep}}/q_u$, where $t_{c1}/t_{cf}$ and $t_{c2}/t_{cf}$ represent the ratios of $t_c$ at the end of the primary creep and the secondary creep to the failure time, $t_{cf}$, respectively. The values of $t_{c1}/t_{cf}$ increase from 0.1 to 0.3 with the values of $q_{\text{creep}}/q_u$ from 0.6 to 1.0. Whereas, the values of $t_{c2}/t_{cf}$ decrease from 0.8 to 0.6 for the same range of $q_{\text{creep}}/q_u$. This implies that, the relative periods of the primary creep and the tertiary creep become longer for larger values of $q_{\text{creep}}/q_u$. Neither on $q_{\text{creep}}/q_u$ nor $T$.

Figure 7 shows the semi-logarithmic relationship between the time to creep failure, $t_{cf}$, and $q_{\text{creep}}/q_u$. The logarithmic values of $t_{cf}$ decrease more or less linearly with $q_{\text{creep}}/q_u$. The data for 24, 40 and 60°C again appear similar, while those for over 60°C shows significantly smaller $t_{cf}$ values.
while that of the secondary creep stage becomes shorter. Moreover, neither $t_{c1}/t_{cf}$ nor $t_{c2}/t_{cf}$ appears to be dependent on $T$.

Figure 9 shows the relationship between the initial axial strain, $e_{a0}$, and $q_{creep}/q_u$. The values of $e_{a0}$ increase from 0.2% to a little over 0.3% with the values of $q_{creep}/q_u$ from 0.6 to 1.0. But they appear to be independent of $T$.

Figure 10 shows the semi-logarithmic relationship between the minimum strain rate, $\dot{e}_{a,min}$, and $q_{creep}/q_u$. The logarithmic values of $\dot{e}_{a,min}$ appear to increase linearly with $q_{creep}/q_u$ at a similar rate for respective temperatures.

Parallel fitting lines are drawn for individual temperatures as expressed by the following equation;

$$\log \dot{e}_{a,min} = 12 \left( \frac{q_{creep}}{q_u} \right) + B$$

where their slopes are set as 12 which is the average value of the slopes of linear regression lines for respective temperatures. As shown in Fig. 11, the intercept $B$ is given as a linear function of $T$ by regression analysis.

$$B = 0.0206T - 14.7$$

When the influence of creep stress ratio, $q_{creep}/q_u$, and temperature, $T$, are taken into account, the creep parameters are grouped into three types. The first type of parameter, $m_3$, is dependent on neither $q_{creep}/q_u$ nor $T$. The second type of parameters, $m_1$, $t_{c1}/t_{cf}$, $t_{c2}/t_{cf}$ and $e_{a0}$ are dependent on $q_{creep}/q_u$, but independent of $T$. Finally, the third type of parameters, $\dot{e}_{a,min}$ and $t_{cf}$, are dependent on both $q_{creep}/q_u$ and $T$. The influences of $T$ become more evident for higher temperatures above 60°C. In the above discussion, it should be reminded that the unconfined compression strength, $q_u$, is defined as a function of temperature, $T$, as Eq. (1).

**RELATIONSHIPS BETWEEN MINIMUM STRAIN RATE AND OTHER CREEP PARAMETERS**

Kato et al. (2004) proposed a creep model for soft rocks, in which all the creep parameters in Eqs. (2) to (7) are determined from the creep stress ratio, $q_{creep}/q_u$. In their model, the influence of temperature was not taken into account, as these creep parameters were found independent of temperature, $T$, in their experimental data for 20–60°C. However, our test results showed that the third type of creep parameters, $\dot{e}_{a,min}$ and $t_{cf}$, are dependent on $T$, especially for $T>60°C$. Other researchers also reported this temperature dependent nature of creep behavior for soft rocks (Yamabe et al., 2001; Jo et al., 2005; Kodama et al., 2005).

In this study, focus is placed on the minimum strain rate, $\dot{e}_{a,min}$, because it is the first creep parameter to be determined in the analysis of creep tests with utmost credibility and least scattering (Shibata et al., 2005).
Figures 12 to 14, thus, show the relationships between \( \dot{e}_{a,\text{min}} \) and other creep parameters obtained under different creep stress ratios, \( q_{\text{creep}}/q_u \), and temperatures, \( T \).

Figure 12 shows the double logarithmic relationships between \( t_{cf}, t_{c1}, t_{c2} \) and \( \dot{e}_{a,\text{min}} \). Note that \( t_{cf} \) and \( \dot{e}_{a,\text{min}} \) depend on both \( q_{\text{creep}}/q_u \) and \( T \) as shown in Figs. 7 and 10, respectively. But, the relationship between \( t_{cf} \) and \( \dot{e}_{a,\text{min}} \) becomes linear and unique, and is dependent on neither \( q_{\text{creep}}/q_u \) nor \( T \). The following equation was then obtained by regression analysis.

\[
\log t_{cf} = -1.01 \log \dot{e}_{a,\text{min}} - 1.37 \tag{10}
\]

The similar relationships between \( t_{c1}, t_{c2} \) and \( \dot{e}_{a,\text{min}} \) are also represented by sub-parallel lines as expressed by the following equations.

\[
\log t_{c1} = -0.92 \log \dot{e}_{a,\text{min}} - 1.68 \tag{11}
\]

\[
\log t_{c2} = -1.03 \log \dot{e}_{a,\text{min}} - 1.59 \tag{12}
\]

Figure 13 shows the semi-logarithmic relationships between \( m_1, m_3 \) and \( \dot{e}_{a,\text{min}} \). While the values of \( m_1 \) increase with log-cycles of \( \dot{e}_{a,\text{min}} \), the values of \( m_3 \) seem to be independent of \( \dot{e}_{a,\text{min}} \). The respective relationships for \( m_1 \) and \( m_3 \) are represented by a hyperbolic function of \( \dot{e}_{a,\text{min}} \) and a constant, respectively.

\[
m_1 = \frac{(\log \dot{e}_{a,\text{min}} - 1) - 0.92 \log \dot{e}_{a,\text{min}} + 2.32}{-0.92 \log \dot{e}_{a,\text{min}} + 2.32} \tag{13}
\]

\[
m_3 = -0.733 \tag{14}
\]

Figure 14 shows the semi-logarithmic relationship between \( e_{a0} \) and \( \dot{e}_{a,\text{min}} \). The values of \( e_{a0} \) increase linearly with log-cycles of \( \dot{e}_{a,\text{min}} \). The following equation was then obtained by regression analysis.

\[
e_{a0} = 0.023 \log \dot{e}_{a,\text{min}} + 0.35 \tag{15}
\]

It is interesting to note that, the relationships between \( \dot{e}_{a,\text{min}} \) and other creep parameters are unique as expressed by Eqs. (10) to (15), and are dependent on neither \( q_{\text{creep}}/q_u \) nor \( T \).

**IMPROVED CREEP MODEL**

**Features of Improved Creep Model**

Improvement was made on the creep model proposed by Kato et al. (2004) to take into account the influence of temperature. This improved model succeeds the basic concept of the original model, that the changes of strain rate with time are typically expressed by Eqs. (2) to (4) for respective creep stages as shown in Fig. 15.

In the original model, all the eight creep parameters are given as functions of the creep stress ratio alone, and no attention was paid to the influence of temperature. However, as explained earlier, the test results on Ohya stone showed that some creep parameters, \( \dot{e}_{a,\text{min}} \) and \( t_{cf} \), are dependent on not only \( q_{\text{creep}}/q_u \) but also \( T \) (Shibata et al., 2004).

In order to take into account the influence of temperature, the method to determine the creep parameters are modified. Creep parameters are divided into two groups. The ones are intrinsic properties, i.e. \( \dot{e}_{a,\text{min}}, t_{cf}, t_{c1}, t_{c2}, m_1, m_3 \) and \( e_{a0} \). And the other is a reference value, i.e. \( e_{a0} \).

The seven intrinsic creep parameters are determined in two steps. Firstly, the minimum strain rate, \( \dot{e}_{a,\text{min}} \), is evaluated from creep stress ratio, \( q_{\text{creep}}/q_u \), and temperature, \( T \), using Figs. 10 and 11 or Eqs. (8) and (9). Secondly, the other six parameters are estimated from the value of \( \dot{e}_{a,\text{min}} \) using Eqs. (10) to (15) which are unique and
dependent on neither $q_{\text{creep}}/q_0$ nor $T$ as shown in Figs. 12 to 14.

For the reference creep parameter, assumptions are made that the creep behavior starts from a certain point $I$ as shown in Fig. 15. Figures 16(a) and 16(b) show the relationships between strain rate and creep time for Ohya stone by this study and Mudstone by Kato et al. (2004), respectively. The extrapolated lines for the primary creep appear to converge at a singular point in early part of the creep behavior. This unique point, $I$, is arbitrarily taken as $(t_{cr}, \dot{\varepsilon}_a) = (1.0 \times 10^{-4} \text{ minute}, 10^w \text{ minute})$ for Ohya stone and $(t_{cr}, \dot{\varepsilon}_a) = (1.0 \times 10^{-4} \text{ minute}, 40^w \text{ minute})$ for Mudstone.

### Accuracy of Determining Creep Parameters

Table 2 compares the coefficient of variations, COV, for the intrinsic creep parameters obtained for both Ohya stone and Mudstone. These values represent the accuracy of the proposed relationships to determine the individual creep parameters, i.e. Figs. 10–11, 12–14 or Eqs. (8) to (15).

The data of Ohya stone shows that, of all the creep parameters except $m_3$, smaller values of COV are obtained for the proposed method than those for Kato et al. (2004)’s method. Similar trends are seen for the data of Mudstone. The reason for this improvement is that, as shown in Figs. 12 to 14, the stronger correlations were found between the minimum strain rate, $\dot{\varepsilon}_{a,\text{min}}$, which reflects the variations of specimens, than the creep stress ratio, $q_{\text{creep}}/q_0$, and the other intrinsic creep parameters.

### Accuracy of Modeling Creep Behavior

Comparison is made for creep behavior between the experiment and the proposed model. Figures 16(a) and 16(b) show the relationships between strain rate, $\dot{\varepsilon}_a$, and creep time, $t_c$, for Ohya stone and Mudstone, respectively. Furthermore, Figs. 17(a) and 17(b) show the relationships between creep strain, $\varepsilon_a$, and creep time, $t_c$, for the respective rocks. The open symbols imply the experimental data, while the broken curves imply the proposed model.

Overall agreement between the experimental data and the proposed model is good, although some extents of deviation are observed for Ohya stone at $T=80^w$ and $q_{\text{creep}}/q_0=0.88$ and for Mudstone at $T=20^w$ and $q_{\text{creep}}/q_0=0.86$. Hence, it may be concluded that the proposed model is valid for both Ohya stone and Mudstone to represent creep behavior under various conditions of creep stress ratios and temperatures.
CONDITION TO CAUSE CREEP FAILURE

Although the condition to cause creep failure is important from the engineering point of view, it is rather difficult to tell whether creep will diminish or enter the tertiary creep leading to failure. The condition of uniaxial creep failure is discussed in the following.

From the concept of the proposed creep model, as seen in Fig. 15, if the strain rate continue to decrease and would not enter the secondary creep, creep failure will not take place. This non-failure condition is realized, if the slope of the line expressed by Eq. (2) for the primary creep, $m_1$, is greater than that of the line expressed by Eq. (11) for the creep time to enter the secondary creep. As shown in Fig. 18, the value of $m_1 = (\frac{\Delta \log \varepsilon_a}{\Delta t_c}) = 1/(-0.921) = -1.09$ and the regression line $m_1 = 0.780\frac{q_{\text{creep}}}{q_u} - 1.43$ provide the critical value of creep stress ratio to bound the failure condition to the non-failure condition as 0.44. Since $m_1$ is not dependent on temperature, this critical value is independent of the temperature.

CONCLUSIONS

Under different temperatures, $T$, from 24°C to 95°C, a series of creep tests was conducted under unconfined condition on a tuffaceous rock, Ohya stone, at creep stress ratios, $q_{\text{creep}}/q_u$, ranging from 0.6 to 1.0. Empirical relationships are investigated for the three creep stages, i.e., primary creep, secondary creep and tertiary creep. The following conclusions are drawn.

(1) The minimum strain rate, $\varepsilon_{a,min}$, and the time to creep failure, $t_{cf}$, are found dependent on both $q_{\text{creep}}/q_u$ and $T$. The influences of $T$ become more evident for higher temperatures above 60°C. However, the rate of acceleration of strain rate in tertiary creep, $m_3$, appear to be dependent on neither $q_{\text{creep}}/q_u$ nor $T$. Furthermore, the rate of deceleration of strain rate in primary creep, $m_1$, and the relative time bounding the three creep stages, $t_{c1}$, $t_{c2}$, are dependent on $q_{\text{creep}}/q_u$; but independent of $T$.

(2) Focus was placed on the minimum strain rate, $\varepsilon_{a,min}$, because $\varepsilon_{a,min}$ is considered as most representative of creep behavior and can be determined with reasonable accuracy and confidence. Unique relationships between $\varepsilon_{a,min}$ and the other creep parameters, $t_{cf}$, $t_{c1}$, $t_{c2}$, $m_1$, $m_3$ and $\varepsilon_{a0}$, are found, and they appear to be dependent on neither $q_{\text{creep}}/q_u$ nor $T$.

(3) In order to take into account the influence of temperature, a new method for determination of the creep parameters was proposed for the Kato et al. (2004)'s creep model. This method was justified as valid, as good agreement was observed between the model and the test results for both Ohya stone and Mudstone under various conditions of creep stress ratios and temperatures.

(4) According to the proposed model and the experimental data, the creep failure will not take place if the creep stress ratio is lower than 0.44 for Ohya stone. Further study is needed by triaxial creep tests under high temperature to investigate the influence of confining pressures. Moreover, the influence of loading rate to the intended creep stress, $q_{\text{creep}}$, should be investigated for more rigorous determination of the relevant creep parameters.

ACKNOWLEDGEMENTS

Sincere thanks are given to Mr. Yuji Miho, a graduate...
student of Yokohama National University, for providing valuable experimental data.

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