Characteristics of Creep Deformation Behavior of Granite under Uniaxial Compression

홍지수[1], 전석원[2]
[1]SK건설 GEOTASK팀, [2]서울대학교 지구환경시스템공학부

1. INTRODUCTION

The time-dependent deformation behavior of rock is one of the most fundamental mechanical properties of the rock material. Investigation and understanding of the TDI deformation processes and mechanisms are thus of key interest in many engineering applications.

Proposals and projects are under way in Korea for nuclear waste disposal and gas storage in rock formations at great depths. Since granite is the most prevalent rock underlying Korean Peninsula and often considered as a strong candidate for hosting the underground repositories, understanding of the time-dependent behavior of granite as well as identification of the associated processes and mechanisms are crucial in assessment of the long-term stability of such rock structures.

In this study, creep tests are performed on Daejeon granite in uniaxial compression under varying stress levels. The effect of moisture content, one of the greatest influencing factors of creep, is investigated by testing both air-dried and fully water-saturated samples. The time-dependent deformation behavior of the rock is analyzed in terms of mechanical and empirical models earlier suggested by other researchers. Based on the experimental results, a constitutive equation of the time-dependent strain is developed for Daejeon granite.

2. BACKGROUND THEORY

Burger's model is considered to best represent the rheological behavior of rock. A standard Burger's model is obtained by combining a Maxwell model and a Kelvin model in series as shown in Figure 2.1(a).A typical strain-time response curve for a Burger material is shown in Figure 2.1(b), which very closely duplicates the primary and secondary creep behavior of real rock materials tested in compression within laboratory settings.

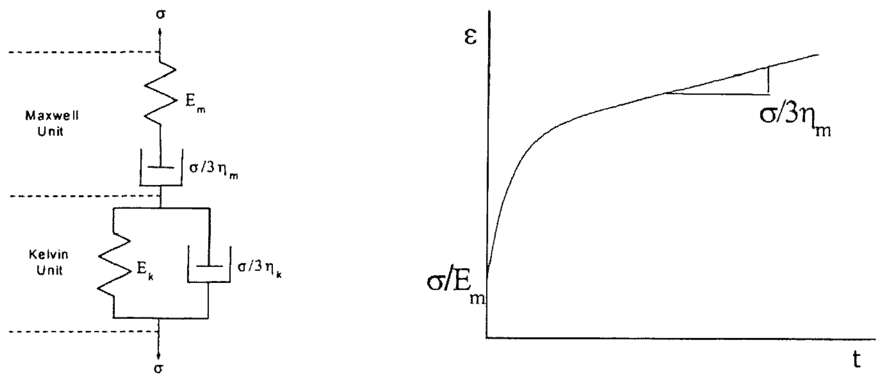


Figure 2.1. Burger material (a) Model (b) Strain-time curve

The total strain of the Burger's solid produced under constant stress s is given by the following relationship

$$\varepsilon = \frac{\sigma}{E_m} + \frac{\sigma}{3\eta_m} t + \frac{\sigma}{E_k}\left(1 - e^{-\frac{E_k t}{3\eta_k}}\right) \tag{2.1}$$

Hardy et al (1969) carried out creep measurements on Indiana limestone, Crab Orchard sandstone and Barre granite. The strain-time curves were fitted to the generalized Burger's model with two Kelvin units

$$\varepsilon = \frac{\sigma}{E_m} + \frac{\sigma}{3\eta_m} t + \sum_{i=1}^{n} \frac{\sigma}{E_{k_i}}\left(1 - e^{-\frac{E_{k_i} t}{3\eta_{k_i}}}\right) \tag{2.2}$$

which resulted in excellent match.

Wawersik and Brown (1973) conducted creep tests on Westerly granite, Nugget sandstone and Tennessee. For air-dried and water-saturated granite, it was found that the axial creep strain could be represented by $\varepsilon_i = 10^c t^n$ and $\varepsilon_{ii} = 10^{c'} t$ where ε_i and ε_{ii} are primary and secondary creep strains, respectively.

Chugh (1974) studied creep of Indiana limestone, Tennesse sandstone and Bare granite and expressed the creep strain in a logarithmic law similar to Grigg's :

$$\varepsilon = A\sigma + B \log t + Ct \tag{2.3}$$

3. EXPERIMENTAL METHOD

All test specimens, testing equipment and procedures used in the actual tests were designed in conformance with the requirements outlined in 'Standard Test Method for Creep of Cylindrical Hard Rock Core Specimens in Uniaxial Compression' suggested by ASTM (1989).

Test specimens were taken from cylindrical cores with depths ranging between 196 m to 292 m. Physical properties of the rock for air-dried and water-saturated samples are tabulated in Table 3.1. Due to the scale of the testing machine, cost and time involved in creep tests of NX-sized granite specimens, a smaller sample size of 25.5 mm diameter was chosen for this study.

Table 3.1.Physical properties of Daejeon granite

	Air-dried	Water-saturated
UCS (MPa)	161.7	117.6
Young's modulus (GPa)	50.9	40.0
Specific gravity	2.64	2.67
Poisson's ratio	0.22	
Apparent porosity (%)	0.75	

A schematic diagram of the creep testing apparatus setup is shown in Figure 3.1. Uniaxial compressive loads were developed using a spring-type loading frame which consists of the following: three guide rods, two fixed plates, two movable plates, and a load bearing spring in between the two movables. The testing machine is designed to have a loading capacity of up to 10 tons and capable of providing compressive loads of 5.7 tons with variation over a period of 250 hours less than 20 kg or within ± 0.18% of the applied load. In all experiments performed to date, the load was maintained to within ± 0.62% of the required test load.

For water-saturated samples, water resistant undercoating was applied and the samples were immersed in water for the whole duration of the test. Throughout the experiment, attempts were made to keep the moisture level and temperature as constant as possible. However, due to environmental control limitations in the laboratory, seasonal variation of moisture level was from 37% to 64% and the variation of temperature was from 21.6℃ to 29.5℃.Daily variations of the moisture level and temperature were within approximately ± 15% and ± 3℃, respectively.

The stresses under which creep tests were performed, varied from 66.3% to 92.2% of UCS_{dry} for air-dried samples and from 52.5% to 76.0% of UCS_{sat} for water-saturated samples. Since the specimens have slightly different values of elastic modulus and the creep behavior is mainly affected by the maximum axial strain occurring in the specimen, the larger strain value displayed between the two strain gages was used as a guide to load the specimen rather than using predetermined incremental load values.

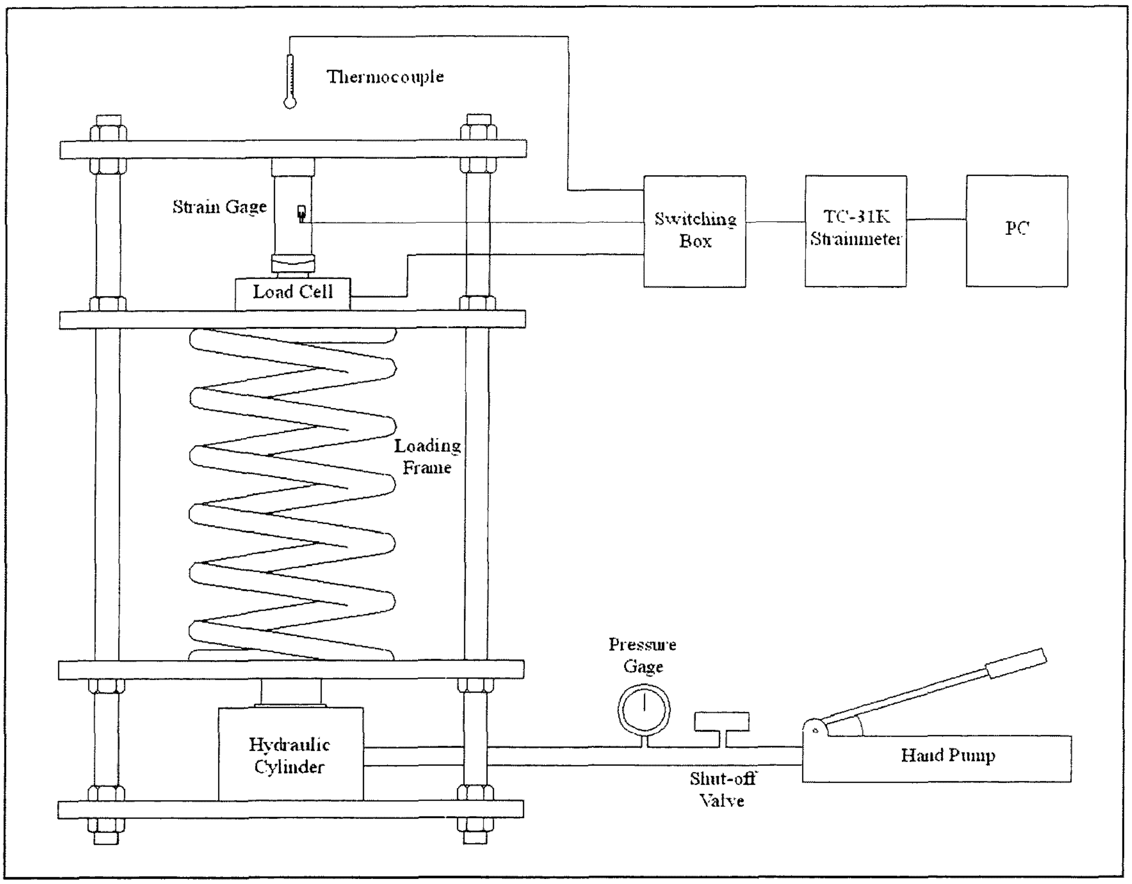


Figure 3.1. Schematic diagram of creep testing apparatus setup

4. RESULTS

In all, creep tests were carried out on sixteen specimens of Daejeon granite, five air-dried and eleven fully water-saturated. Each creep curve was fitted statistically to the Burger's, Wawersik and Brown's, and Chugh's model and coefficients of the corresponding equations were determined. Effects of water on those parameters as well as on time-dependent strength of the rock are discussed.

4.1 Creep Curves

The creep behavior of Daejeon granite exhibited distinctively the well-known three stages of primary, secondary and tertiary creep. Creep curves of axial strains vs. time for all sixteen samples are shown in Figure 4.1 in which ultimate failure of the rock following tertiary creep is denoted by an asterisk (*). Most air-dried samples terminated in creep fracture even at relatively low stress levels, as low as 66.3% of UCS_{dry}. The lowest stress level at which water-saturated sample failed was 55.1% of UCS_{sat}.

For water-saturated samples, there existed two groups of specimens which are referred to as groups of water-saturated I and II specimens, represented by blue solid and black dashed lines in Figure 4.1, respectively. It was found that the elasticity modulus of water-saturated I samples were slightly higher than those of water-saturated II samples, which may be possibly due to low porosity or low degree of saturation.

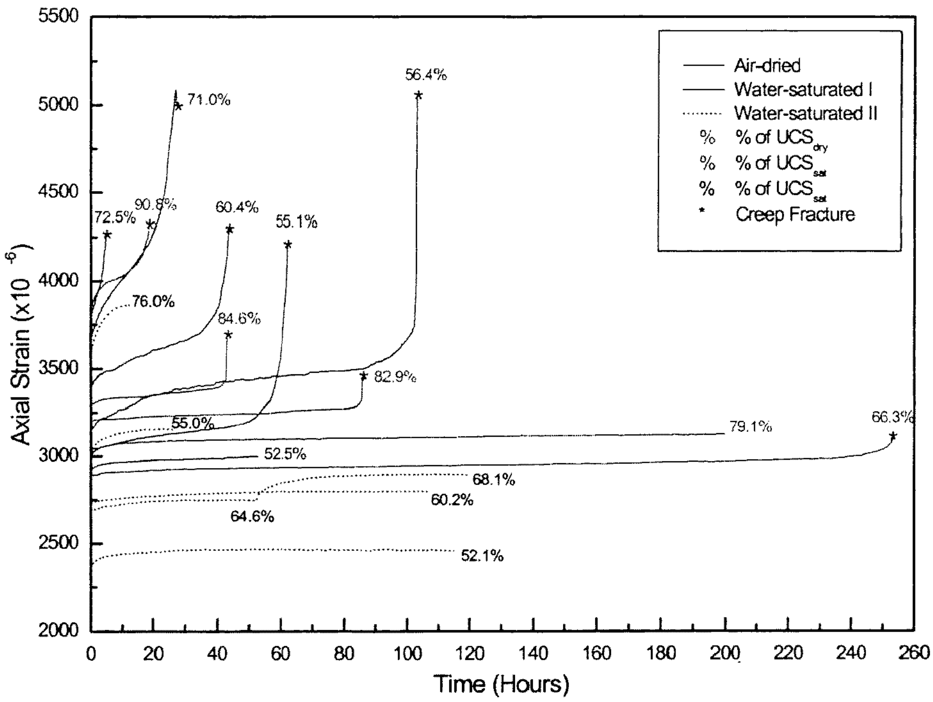
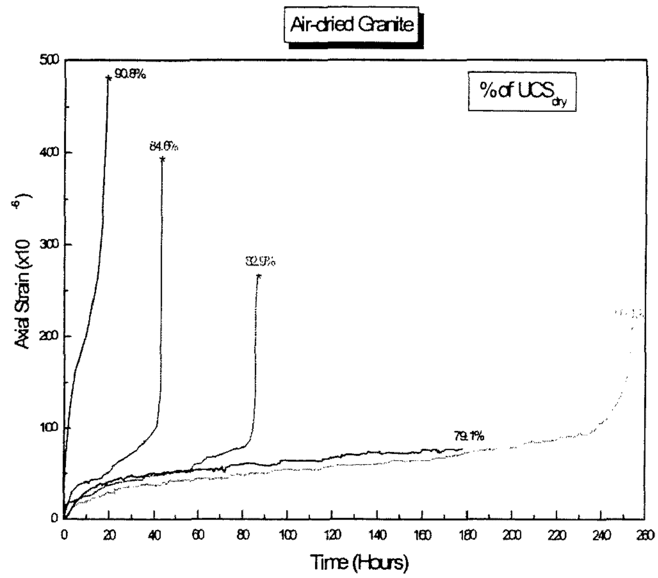
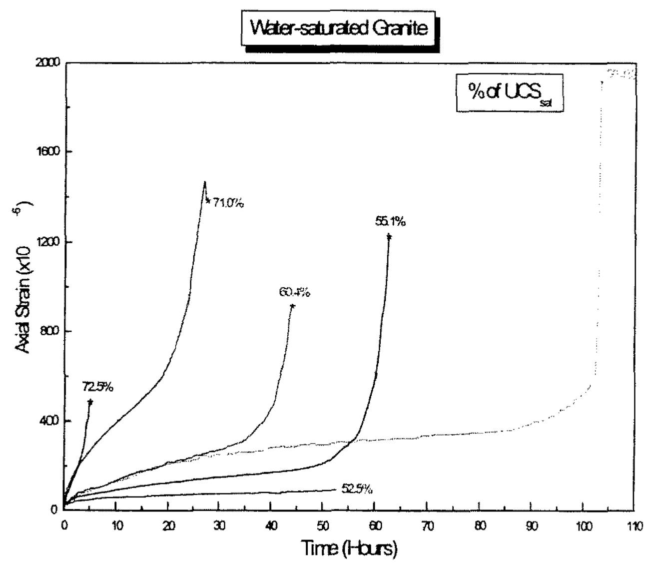


Figure 4.1 Time vs. axial creep strain

Since the creep strains are small compared to the instantaneous response of the rock to the stress at which creep is observed, the instantaneous strains are referenced as zero in Figure 4.2. As evident in comparison of the two graphs, saturation and immersion in water markedly increased the total amount of creep strain as well as the secondary creep rate. Water-saturation also drastically reduced the threshold stress level at which the onset of secondary creep was observable, from 107 MPa for air-dried to 62 MPa for water-saturated samples.



(a) air-dried granite



(b) water-saturated granite

Figure 4.2. Creep curves of Daejeon granite

4.2 Creep Parameters

Values of four parameters associated with the Burger's model were determined from the curve fittings for a number of stress levels. Young's moduli for the Maxwell material, $E_{Maxwell}$, is independent of stress, but dependent on the moisture content of the rock instead. Young's moduli for the for the Kelvin material, E_{Kelvin} , decrease with greater amounts of primary creep strain. However, due to a considerable scatter in values of E_{Kelvin} , more experiments need to be carried out in order to draw a specific conclusion. Viscosity coefficient of the Maxwell unit, $\eta_{Maxwell}$, is decreases with the applied stress. Viscosity coefficient of the Kelvin unit, η_{Kelvin}, tend to decrease with the applied stresses for both air-dried and water-saturated samples. It is worth noting that the stress-dependency of both parameters $\eta_{Maxwell}$ and η_{Kelvin} are far more sensitive for air-dried samples than for water-saturated samples.

Values of three parameters associated with the logarithmic creep equation defined by Chugh (1974) were determined from the curve fittings for a number of stress levels. Parameter A is stress-independent and similar for each group of air-dried and water-saturated samples. Although masked by a scatter, parameter B tends to increase with the increasing stress levels. Parameter C tends to increase exponentially with the increasing stress levels.

Figure 4.3 present data for the three parameters of Wawersik & Brown's (1973) empirical relations for primary and secondary creep of Westerly granite. The results from creep tests of Daejeon granite are in excellent match with their results.

The parameter c shows a linear relationship with the applied stress level for both air-dried and water-saturated samples, whereas there seems no correlation between the parameter n and the stress. As in the case of c, the parameter c′ appears to vary linearly with stress. The linear variability of c′ with σ appears somewhat more distinct for water-saturated samples than for air-dried samples.

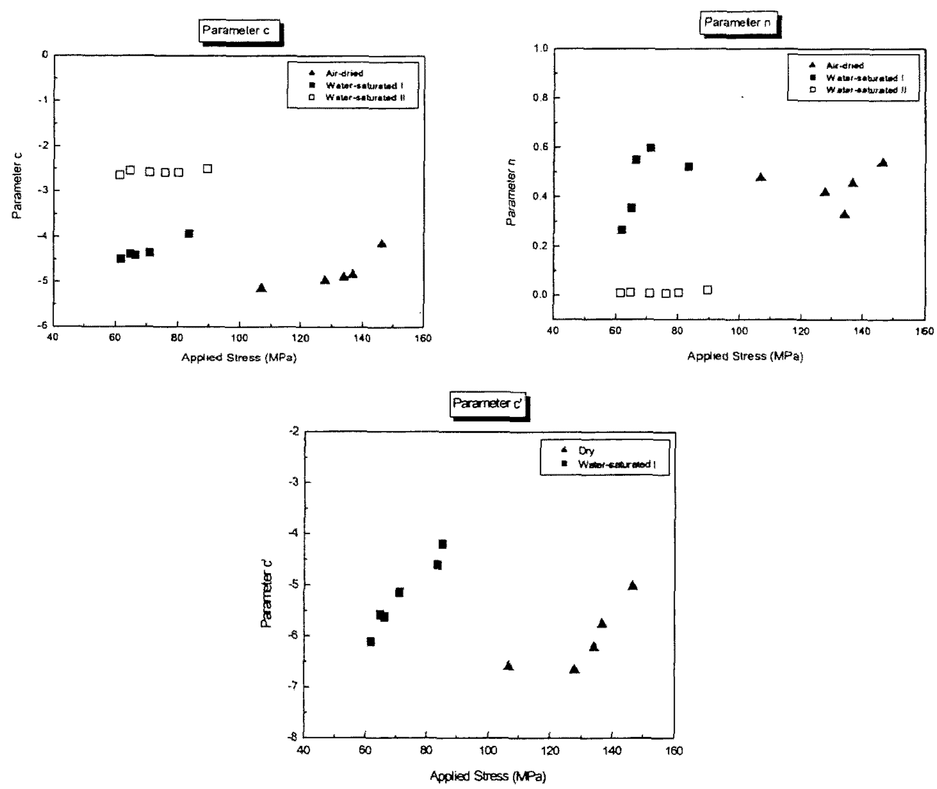


Figure 4.3. Values of parameters for Wawersik & Brown's model

4.3. Derivation of Time Dependent Stress-Strain Relation

From the description of primary and secondary creep as expressed by Wawersik and Brown, $\varepsilon_c = 10^c t^n$ and $\dot{\varepsilon}_s = 10^{c'}$, and following their procedures, time dependent stress-strain laws can be derived for Daejeon granite. Since the stress ranges under which creep occurs and the range of values of related parameters c, n and c′ are different depending on the moisture contents of the rock, a time dependent stress-strain relation is established separately for each air-dried and fully water-saturated state of Daejeon granite.

Taking into account the average value of n and the stress dependency of c and c′, the time dependent strain of air-dried and water-saturated Daejeon granite under constant stress, σ, can be described as follows:

$$\varepsilon_{dry} = 1.13\times10^{-9} e^{7.08\frac{\sigma}{\sigma_{dry}^{*}}} t^{0.393} + 2.531\times10^{-12} e^{9.718(\frac{\sigma}{\sigma_{dry}^{*}})} t \tag{4.1}$$

$$\varepsilon_{sat} = 6.76\times10^{-7} e^{3.61\frac{\sigma}{\sigma_{sat}^{*}}} t^{0.457} + 6.113\times10^{-11} e^{9.384(\frac{\sigma}{\sigma_{sat}^{*}})} t \tag{4.2}$$

where σ_{dry}^{*} = 97.02 MPa, σ_{sat}^{*} = 58.80 MPa, $\frac{\sigma}{\sigma_{dry}^{*}} \le 1.\dot{6}$, and $\frac{\sigma}{\sigma_{sat}^{*}} \le 2$.

Based on the developed stress-strain relations, the time dependent deformation of air-dried and fully water-saturated Daejeon granite can be estimated given the applied stress level. It is necessary, though, to further check the validity of these relations by conducting a number of creep experiments covering different specimen sizes as well as under a broader range of stress levels. The influence of temperature and pore water pressure should also be investigated in order to better understand the time dependent behavior of the rock.

5. CONCLUSIONS

1) The creep behavior of Daejeon granite exhibits three distinctive stages of primary, secondary and tertiary creep. It is observed that primary creep period is usually less than 24 hours and the secondary creep rate increases with the applied stress levels.

2) Saturation and immersion of the test specimen in water markedly increased the total creep strain of Daejeon granite. The presence of water also significantly increased the secondary creep rate and reduced the time-to-failure of Daejeon granite.

3) The experimental curves are fitted to three models: Burger's, Chugh's, and Wawersik & Brown's model. All three models well describe the primary and secondary creep behavior of Daejeon granite and a number of the parameters determined for each model are dependent on stress and influenced by presence of water.

4) An empirical relation between the applied stress and the time-dependent strain is established separately for each air-dried and fully water-saturated Daejeon granite:

$$\varepsilon_{dry} = 1.13\times10^{-9} e^{7.08\frac{\sigma}{\sigma_{dry}}} t^{0.393} + 2.531\times10^{-12} e^{9.718(\frac{\sigma}{\sigma_{dry}})} t$$

$$\varepsilon_{sat} = 6.76\times10^{-7} e^{3.61\frac{\sigma}{\sigma_{sat}}} t^{0.457} + 6.113\times10^{-11} e^{9.384(\frac{\sigma}{\sigma_{sat}})} t$$

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