Understanding the time-dependent behavior of rocks is important for ensuring the long-term stability of underground structures. Aspects of such a time-dependent behavior include the loading-rate dependency of Young’s modulus, strength, creep, and relaxation. In particular, the loading-rate dependency of Young’s modulus of rocks has not been fully clarified. In this study, four different types of rocks were tested, and the results were used to analyze the loading-rate dependency of Young’s modulus and explain the underlying mechanism. For all four rocks, Young’s modulus increased linearly with a tenfold increase in the loading rate. The rocks showed the same loading-rate dependency of Young’s modulus. A variable-compliance constitutive equation was proposed for the loading-rate dependency of Young’s modulus, and the calculated results agreed well with measured values. Irrecoverable and recoverable strains were separated by loading-unloading-reloading tests at preset stress levels. The constitutive equations showed that the rate of increase in Young’s modulus increased with the irrecoverable strain and decreased with increasing stress. The increase in the irrecoverable strain was delayed at high loading rates, which was concluded to be the main reason for the increase in Young’s modulus with an increasing loading rate.

1. Introduction

For rocks, the strength is known to increase with the loading rate (i.e., loading-rate dependency) [1–4], the strain increases under constant stress (i.e., creep), and stress decreases under a constant strain (i.e., relaxation) [5, 6]. In various tests, the displacement rate affects the measured strength, elastic modulus, cohesive force, internal friction angle, and fracture mode [7, 8]. The loading-rate dependency of the strength has been comprehensively studied through uniaxial compression and indirect tensile tests [9] and shear and triaxial compression tests [10]. In particular, a 15-year creep test was performed on Taffe tuff at a stress level of 30% [11]. These studies showed that understanding the time-dependent behavior of rocks is important for ensuring the long-term stability estimating the lifetime of underground structures [12]. The basic characteristics and theory of relaxation have been used to explain strain hardening and softening [13]. Some scholars have suggested that creep and relaxation are not fully independent; Fukui et al. [14] analyzed the coupling characteristics of creep and relaxation to develop the concept of generalized relaxation.

However, the loading-rate dependency of Young’s modulus of rocks has not been fully clarified. In a previous study, the data scatter for the loading-rate dependency of Young’s modulus was reduced by normalizing Young’s modulus at 50% of the peak strength against Young’s modulus at 10% of the peak strength, which was first obtained at a predetermined loading rate. For Sanjome andesite, Young’s modulus was shown to increase by 2% with a tenfold increase in the loading rate; meanwhile, Young’s moduli of marble, granite, and sandstone decreased slightly with an increasing loading rate [15]. Only a few studies have explained the microcrack evolution, associated deformation, and strength properties of rocks with various strain rates [16]. Xu and Dai [17] showed that Young’s and shear moduli exhibited some loading-path
dependency under quasistatic loading but were insensitive to the loading path at high loading rates. Both the strength and Young’s modulus of the rock-like specimens strongly depended on the strain rate. Yan et al. [18] numerically studied the rate-dependent cracking behavior of single-flawed rock specimens and found that the initiation angle and fracture process zone are significantly affected by the strain rate.

In this study, four rocks were tested under uniaxial compression, direct tension, and indirect tension to evaluate Young’s moduli at different loading rates. The values of Young’s moduli from loading–unloading tests in literature [15] were statistically analyzed, and the irrecoverable and recoverable strains were separated [19]. The results were used to develop constitutive equations that represent the loading-rate dependency of Young’s modulus and clarify the underlying mechanism.

2. Materials and Methods

2.1. Specimen Description. Wawersik and Fairhurst [20] divided rocks into two classes based on the complete stress-strain curve in the postfailure region, as shown in Figure 1. Class I rocks always have a negative slope in the postfailure region, whereas Class II rocks always have a positive slope in the postfailure region.

Four types of rocks were tested: Tage tuff (Class I), Ogino tuff (Class I), Emochi andesite (Class II), and Jingkou sandstone (Class II). Tage tuff was obtained from Tochigi Prefecture in Japan and mainly comprised albite, feldspar, and small amounts of calcite. Ogino tuff was obtained from Fukushima Prefecture in Japan and mainly comprised zeolite, mullite, clay, and small amounts of plagioclase and biotite. Emochi andesite was obtained from Fukushima Prefecture in Japan and mainly comprised plagioclase, pyroxene, and a small amount of biotite. Jingkou sandstone was obtained from Chongqing in China and mainly comprised quartz, feldspar, vermiculite, and muscovite. Table 1 lists the basic physical and mechanical parameters of the rocks. Tage tuff and Ogino tuff had a higher saturated water content than Emochi andesite and Jingkou sandstone but a lower peak strength.

The specimens were obtained by drilling blocks of rock that were then cut into cylinders with diameters of 25 mm and heights of 50 mm for the uniaxial compressive and uniaxial direct tensile tests. The specimens for the indirect tensile tests (i.e., Brazilian splitting tests) had a diameter of 25 mm and a height of 12.5 mm. To ensure accurate data, the specimens were polished by a 55-C0201/C polishing machine (Controls Group, Milan, Italy) according to International Society for Rock Mechanics and Rock Engineering (ISRM) standards to ensure flatness, verticality, and parallelism. The surfaces of the polished specimens had a flatness of ≤0.01 mm. More than eight specimens of each rock type were employed for each testing condition. The scatter in the test data was addressed by calculating the average value from the eight specimens.

2.2. Control Method. The strain rate-controlled method was used to test Class I rocks (i.e., Tage tuff and Ogino tuff), as shown in Figure 1. The stress-feedback method [21] was used to test the Class II rocks (i.e., Emochi andesite and Jingkou sandstone). The control formula is given by

$$\varepsilon - \alpha \cdot \frac{\sigma}{E} = C \cdot t = f(t),$$

where $t$ is the time, $f(t)$ is a function of time, $C$ is the loading rate, $E$ is Young’s modulus of the rock, $\varepsilon$ and $\sigma$ are the strain and stress, respectively, and $\alpha$ is the ratio of the stress feedback. The Class II rocks were tested at $\alpha = 0.3$ with variable-resistance technology, in which a loading cell and linear variable differential transformer were used to collect stress and strain signals in the servo-controller. The values of the strain and stress were controlled by the variable resistances $VR_1$ and $VR_2$, respectively. The ratio between $VR_1$ and $VR_2$ is represented by $\beta$. $\alpha$ is the ratio of the stress feedback and is expressed as $a = k \cdot \beta$, where $k$ is a constant.

The stress signal value is $\alpha \cdot \beta / E$, and the strain signal value is $\varepsilon$. A constant linear combination of the stress and strain (i.e., $\varepsilon - \alpha \cdot \beta / E$) was used in the Add/Sub amplifier as the feedback signal in a closed loop. This allows the stress-feedback method to obtain a precise value for Young’s modulus.

All stress-strain curves were obtained at loading rates of $C = 1 \times 10^{-6}, 1 \times 10^{-5}, 1 \times 10^{-4}, \text{ and } 1 \times 10^{-3} \text{s}^{-1}$ for uniaxial compression; $1 \times 10^{-5}, 1 \times 10^{-4}, \text{ and } 1 \times 10^{-3} \text{s}^{-1}$ for direct tension; and $5 \times 10^{-6}, 5 \times 10^{-5}, 5 \times 10^{-4}, \text{ and } 5 \times 10^{-3} \text{mm/s}$ for indirect tension. For the uniaxial direct tensile tests, the specimens were prepared as follows: the top end of the specimen was liberally coated with epoxy resin, and the specimen was affixed to the surface of the upper plate. Then, a slight load was placed on the specimen for 24 h. The bolt portion of the plate was then screwed into the ram head, and the bottom end of the specimen was affixed to a similar lower plate. Then, a slight load was placed on the specimen for 24 h prior to the tensile test.

2.3. Modulus Calculation Method. For uniaxial compressive tests, the tangent modulus $E$ was used to represent Young’s modulus. For the uniaxial direct tensile tests, the initial modulus $E_{TT}$ was used to represent Young’s modulus; this is the slope of the line passing through the origin point and tangent to the prefailure curve. For the uniaxial indirect tensile tests (Brazilian splitting tests), the splitting modulus $E_{TT}$ was obtained as follows:

$$E_{TT} = \frac{F/S_{ABCD}}{D_p/D_d},$$

where $E_{TT}$ is the splitting modulus, $F$ is the axial force, $S_{ABCD}$ is the area of the meridional plane, $D_p$ is the displacement, and $D_d$ is the specimen diameter. Figure 2 shows the meridional plane of the indirect tensile test specimens.

3. Experimental Results

3.1. Stress-Strain Curves under Different Loading Conditions. Figure 3 shows the stress-strain curves of the Class I rocks under uniaxial compression, and Figure 4 shows the corresponding stress-strain curves of the Class II rocks. The Class I and Class II rocks showed the same loading-rate...
dependency. Figure 5 shows the stress-strain curves and stress-irrecoverable strain curves of Tagetuff (Class I) under uniaxial direct tension. The irrecoverable strain was separated from the slope of the unloading curve. These curves showed a clear loading-rate dependency. Figure 6 shows the force-displacement curves of Tagetuff (Class I) and Jingkou sandstone (Class II) under indirect tension. The load sharply dropped at the peak, but a loading-rate dependency can clearly be observed. The stress-strain curves of the four rocks at different loading rates were used to analyze further the loading-rate dependency of Young’s modulus.

3.2. Loading-Rate Dependency of Young’s Modulus under Uniaxial Compression. Figure 7 shows double-logarithmic plots of the loading-rate dependency of Young’s modulus for the four rocks at stress levels of 30%, 50%, and 70%. For the Class I rocks, Young’s modulus increased with the loading rate. For Tagetuff, the increase was greatest at a stress level of 50% and least at 70%. For Ogino tuff, the increase was greatest at 50% and least at 30%. For the Class II rocks, Young’s modulus also increased with the loading rate. For Emochi andesite, the increase was greatest at 70% and least at 30%. The increases only slightly differed at stress values of 50% and 70%, and the two curves almost coincided. Linear relaxation was observed between Young’s modulus and loading rate for all four rock types. The maximal correlation coefficient was 0.9947 for $E_{70}$ of Ogino tuff, and the minimal coefficient was 0.6385 for $E_{70}$ of Emochi andesite. Figure 8 shows the relationship between Young’s modulus and loading rate for the four rock types. For Tagetuff, Young’s modulus had average values of 4.40, 4.55, and 4.12 GPa at 30%, 50%, and 70%, respectively, of the maximum stress. This corresponds to increases of 1.57%, 1.38%, and 1.92%, respectively, in Young’s modulus for each tenfold increase in the loading rate. For Ogino tuff, the average values of Young’s modulus were 4.18, 4.56, and 4.33 GPa, respectively, at the three stress levels. This corresponds to increases of 1.57%, 1.38%, and 1.92%, respectively, in Young’s modulus for each tenfold increase in the loading rate. For Emochi andesite, the average values of Young’s modulus were 8.16, 8.80, and 8.82 GPa, respectively, which correspond to increases of 3.17%, 3.26%, and 2.95%, respectively, for each tenfold increase in the loading rate. For Jingkou sandstone, the average values of Young’s modulus were 10.80, 12.42, and 12.32 GPa, respectively, which correspond to increases of 1.88%, 1.76%, and 1.78%, respectively, for each tenfold increase in the loading rate.

These results show that Young’s modulus increased linearly with each tenfold increase in the loading rate for both Class I and Class II rocks, and the same loading-rate dependency fitted for each rock type.

| Rocks                | Density (g/cm³) | Saturated water content (%) | UCS* (MPa)  | $E^*$ (GPa) | $v^*$ |
|----------------------|----------------|----------------------------|-------------|------------|-------|
| Tagetuff             | 1.74           | 15.04                      | 22.26       | 3.83       | 0.32  |
| Ogino tuff           | 1.81           | 10.53                      | 27.35       | 4.02       | 0.31  |
| Emochi andesite      | 2.11           | 6.98                       | 77.50       | 10.05      | 0.25  |
| Jingkou sandstone    | 2.29           | 4.81                       | 67.49       | 11.89      | 0.24  |

*UCS: uniaxial compression strength; $E$: Young’s modulus; $v$: Poisson’s ratio.
Figure 3: Uniaxial compressive stress-strain curves for Class I rocks at different strain rates: (a) Tage tuff and (b) Ogino tuff.

Figure 4: Uniaxial compressive stress-strain curves for Class II rocks at different strain rates: (a) Emochi andesite and (b) Jingkou sandstone.

Figure 5: (a) Stress-strain and (b) stress-irrecoverable strain curves for Tage tuff (Class I) at different loading rates for the uniaxial direct tensile test.
dependency was observed for Young’s modulus of all rocks. However, Class II rocks showed greater increases in Young’s modulus than Class I rocks. This may be related to rock strength, rock gaps, and weak internal surfaces.

3.3. Loading-Rate Dependency of Young’s Modulus under Uniaxial Tension. Figure 9 shows the loading-rate dependency of Young’s modulus for Tage tuff (Class I) in direct tension. As noted in Section 2.3, the initial modulus \( E_{\text{DT}} \) was taken as Young’s modulus. The relationship between Young’s modulus and loading rate is nearly linear on the double-logarithmic plot with a correlation coefficient of 0.9959. Figure 9 also shows the loading-rate dependency of Young’s modulus in indirect tension, which is represented by the splitting modulus \( E_{\text{TT}} \) from equation (2). The splitting modulus and loading rate showed a linear relationship in the double-logarithmic plot with a correlation coefficient of 0.9309. Thus, Young’s modulus of Class I rocks under uniaxial direct and indirect tension increased linearly with a tenfold increase in the loading rate. For Tage tuff, the ratio \( K_1 \) between Young’s modulus and initial modulus was 1.086, and the ratio \( K_2 \) between Young’s modulus and splitting modulus was 7.983. The ratio \( K \) can be used to quantitatively analyze the loading-rate dependency of Young’s modulus under different loading conditions and is important for predicting the engineering properties of rock masses.

4. Constitutive Equation and Calculated Results

4.1. Variable-Compliance Constitutive Equation. Figure 10 shows the nonlinear Maxwell model that was used to simulate the loading-rate dependency of Young’s modulus. The following constitutive equations were proposed:

\[ \varepsilon = \varepsilon_1 + \varepsilon_3, \]

\[ \frac{d\varepsilon_1}{dt} = \alpha_1 \varepsilon_1^{m_1} \sigma^{n_1}, \]

\[ \varepsilon_3 = \lambda \sigma, \]

where \( \lambda \) is the variable compliance. Its initial value is the reciprocal of the spring modulus with the parameter ranges of \( \alpha_1 > 0, \alpha_2 > 0, +\infty > m_1 > -\infty, +\infty > m_3 > -\infty, n_1 \geq 1, \) and \( n_3 \geq 1. \) When \( n_1 = n_3 = 1, \) the model reflects the behavior of materials with Newtonian viscosity. When \( n_1 \geq 1 \) and \( n_3 \geq 1, \) the model is accurate for materials with ordinary viscosity. In addition, \( t \) is the time; \( \varepsilon \) and \( \sigma \) are the strain and stress, respectively; and \( \varepsilon_1 \) and \( \varepsilon_3 \) are the irrecoverable and recoverable strains, respectively.

Equation (7) is obtained from equations (3)–(6) to give Young’s modulus at a preset stress level:

\[ E = \frac{d\sigma}{d\varepsilon} = \frac{1/\lambda_0}{1 + (A'/\lambda_0) \cdot C^\alpha}, \]

\[ A' = \alpha_1^{1/m_1+1} \left( \frac{n_1 + 1}{m_1 + 1} \right)^{m_1/m_1+1} \cdot \left\{ \left[ \frac{n_3 + 1}{a_3 (m_3 - 1) \cdot \lambda_0^{m_3}} \right]^{1/n_3+1} \right\}^{n_3 - m_3/m_3+1}, \]

\[ n' = \frac{n_1 - m_1 - n_3 - 1}{(n_3 + 1) (m_1 + 1)}, \]

where \( C \) is the loading rate, \( A' \) and \( n' \) are constants, and \( \sigma_{\text{pol}} \) is the preset stress level.

4.2. Calculated Parameters. In previous studies [10, 22], a method was introduced for calculating the parameters \( \alpha_1, \alpha_2, m_1, m_3, n_1, \) and \( n_3, \) where the value of \( n_3 \) is obtained in tests at a constant or alternating loading rate. Then, \( n_1 = n_3 \) was assumed for numerical simulations, and the loading-rate dependency of the strength for porous rocks and the generalized relaxation behavior of Kawazu tuff were simulated. Here, a new method is proposed for calculating the value of \( n_1 \) by using equation (7) to
simulate the loading-rate dependency of Young’s modulus. Table 2 presents the parameter values calculated for the four rock types.

4.3. Calculated Results of Young’s Modulus. Equation (7) was used to calculate $\Delta E/E$ for each tenfold increase in the loading rate. The results for the four rock types are presented in Figure 11 and Tables 3–6. The calculated values agreed with the measured results. For Tage tuff (dry condition), Table 3 indicates that the measured values of $\Delta E/E$ at stress levels of 30%, 50%, and 70% were 0.0160, 0.0145, and 0.0196, respectively, uniaxial compression; the calculated values
Figure 8: Relationship between Young’s modulus and loading rate for the four rocks.

Figure 9: Loading-rate dependency of Young’s modulus for Tage tuff under direct and indirect tension.

Figure 10: Nonlinear Maxwell model.
were 0.0166, 0.0180, 0.0189, respectively. Under direct tension and indirect tension, the measured values were 0.0264 and 0.0200, respectively, and the calculated value for direct tension is 0.0211. In literature [15], the experimental value for $\Delta E/E$ was 0.0760 under wet conditions and 0.0470 under dry conditions. $Q_h$, $\Delta E/E$ was clearly greater under wet conditions than under dry conditions for Tage tuff.

For Ogino tuff (dry condition), Table 4 indicates that the measured values of $\Delta E/E$ at stress levels of 30%, 50%, and 70% were 0.0295, 0.0371, and 0.0473, respectively, under uniaxial compression. $Q_h$ calculated results were 0.0375, 0.0135, and 0.0355, respectively. For direct tension, the initial modulus was used to separate their recoverable strain. Tables 2–5 present the measured values of the irrecoverable strain.

The correlation coefficient of Young’s modulus with strength is given by $(\Delta E/E)/(\Delta \sigma/\sigma)$. Figure 13 shows the relation between $(\Delta E/E)/(\Delta \sigma/\sigma)$ and $\varepsilon_{t}/\varepsilon$ from Tables 3–6, which is approximated by equation (10) for rocks under uniaxial compression and tension:

$$\frac{\Delta E}{E} \approx \left( \frac{\varepsilon_1}{\varepsilon} \right) \cdot \left( \frac{\Delta \sigma}{\sigma} \right).$$ (10)

Equation (7) can be used to obtain

$$\frac{\Delta E}{E} = \left\{ 1 - \frac{1}{10^j (m_{i+1})^j} \right\} \cdot \frac{\varepsilon_1}{\varepsilon_1 + \lambda \sigma_{psl}}.$$ (11)

The constitutive equations and test results showed that $\Delta E/E$ is related to the irrecoverable strain $\varepsilon_1$ and preset stress level $\sigma_{psl}$. The rate of increase in Young’s modulus increases with the irrecoverable strain, and it decreases with increasing stress. The irrecoverable strain showed a delay at high loading rates, which may explain the increase in Young’s modulus with an increased loading rate.

## 5. Discussion

In this study, loading–unloading–reloading tests were performed at preset stress levels of 30%, 50%, and 70% of the peak strength to separate the irrecoverable strain under uniaxial compression. Figure 12 shows the average values of the unloading modulus $K_u$ at stress levels of 30%, 50%, and 70%. The unloading modulus values for Tage tuff, Ogino tuff, Emochi andesite, and Jingkou sandstone were 5.55, 7.8, 12, and 11.6 GPa, respectively. For direct tension, the initial modulus was used to separate the irrecoverable strain. Additional test data on Young’s modulus will be obtained in future research.
Table 3: Statistical results for the measured and calculated Young’s moduli of Tage tuff.

| Source | Type       | E₀      | E₅₀     | E₇₀     | E₅₁T    | E₅₁T    | E₅₀     | E₅₀     |
|--------|------------|---------|---------|---------|---------|---------|---------|---------|
|        |            |         |         |         |         |         |         |         |
|        | Δσ/σ       | 0.0526  | 0.0607  | —       | 0.0560  | 0.1010  |         |         |
|        | ε₁/ε       | 0.2804  | 0.2383  | 0.2241  | 0.3605  | —       | —       | —       |
|        | (Δσ/σ × ε₁/ε) | 0.0142  | 0.0125  | 0.0118  | 0.0219  | —       | —       | —       |
|        | ΔE/E       | 0.0160  | 0.0145  | 0.0196  | 0.0264  | 0.0200  | 0.0470  | 0.076   |
|        | (ΔE/E)*    | 0.0166  | 0.0180  | 0.0189  | 0.0211  | —       | —       | —       |

Table 4: Statistical results for the measured and calculated Young’s moduli of Ogino tuff.

| Source | Type       | E₀      | E₅₀     | E₇₀     | Okubo et al. |
|--------|------------|---------|---------|---------|--------------|
|        |            |         |         |         | Dry          |
|        | Δσ/σ       | 0.0497  |         |         |              |
|        | ε₁/ε       | 0.5693  | 0.5339  | 0.5144  |              |
|        | (Δσ/σ × ε₁/ε) | 0.0283  | 0.0265  | 0.0256  |              |
|        | ΔE/E       | 0.0295  | 0.0371  | 0.0473  |              |
|        | (ΔE/E)*    | 0.0375  | 0.0135  | 0.0355  |              |

Table 5: Statistical results for the measured and calculated Young’s moduli of andesite.

| Source | Type       | E₀      | E₅₀     | E₇₀     | Okubo et al. |
|--------|------------|---------|---------|---------|--------------|
|        |            |         |         |         | Dry          |
|        | Δσ/σ       | 0.0521  | 0.0620  | 0.0620  |              |
|        | ε₁/ε       | 0.4903  | 0.4299  | 0.3915  |              |
|        | (Δσ/σ × ε₁/ε) | 0.0255  | 0.0224  | 0.0204  |              |
|        | ΔE/E       | 0.0335  | 0.0347  | 0.0321  |              |
|        | (ΔE/E)*    | 0.0207  | 0.0204  | 0.0201  |              |

Table 6: Statistical results for the measured and calculated Young’s moduli of sandstone.

| Source | Type       | E₀      | E₅₀     | E₇₀     | Okubo et al. |
|--------|------------|---------|---------|---------|--------------|
|        |            |         |         |         | Dry          |
|        | Δσ/σ       | 0.0526  | 0.0613  |         |              |
|        | ε₁/ε       | 0.3508  | 0.2456  | 0.1792  | 0.1221       |
|        | (Δσ/σ × ε₁/ε) | 0.0215  | 0.0153  | 0.0110  | —            |
|        | ΔE/E       | 0.0192  | 0.0180  | 0.0182  | 0.0170       |
|        | (ΔE/E)*    | 0.0206  | 0.0087  | 0.0206  | —            |

* (Δσ/σ): measured stress for a tenfold increase in the loading rate; (ΔE/E): measured Young’s modulus for a tenfold increase in the loading rate; (ΔE/E)*: calculated Young’s modulus for a tenfold increase in the loading rate; ε and ε₁: measured failure strain and irrecoverable strain at the preset point, respectively. Source: experimental data in the study and from [15].
6. Conclusions

The loading-rate dependency of Young’s modulus for Class I and Class II rocks was systematically studied through laboratory tests, and a variable-compliance constitutive equation was developed. The main conclusions are as follows:

(1) Precise test data for Young’s moduli of four rock types were obtained under uniaxial compression by improving the precision of the specimen dimensions. The initial modulus and split modulus of Tage tuff under direct and indirect tension were also obtained. Regardless of the test method, Young’s modulus showed the same law of loading-rate dependency.

(2) Irrecoverable and recoverable strains were separated by loading-unloading-reloading tests at preset stress levels, where the slope of the unloading secant curve was used as the elastic constant.

(3) The variable-compliance constitutive equation was used to simulate the loading-rate dependency of Young’s modulus. The calculated results showed good agreement with the measured values.

(4) The constitutive equations and test data showed that the rate of increase in Young’s modulus increased with the irrecoverable strain and decreased with increasing stress. The irrecoverable strain showed a delayed increase at high loading rates, which may be the main reason for the increase in Young’s modulus with an increasing loading rate.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

The authors would like to thank the Natural Science Foundation of Chongqing, China (cstc2019jcyj-msxmX0488 and cstc2021jcyj-msxm3199), the Science and Technology Research Program of Chongqing Municipal Education Commission (KJQN201901338), and the China Postdoctoral Science Foundation (2021M693751) for their financial support.

References

[1] O. Sano, I. Ito, and M. Terada, “Influence of strain rate on dilatancy and strength of Oshima granite under uniaxial compression,” *Journal of Geophysical Research: Solid Earth*, vol. 86, no. B10, pp. 9299–9311, 1981.

[2] K. Fukui, S. Okubo, and Y. Nishimatsu, “Generalized relaxation behavior of rock under uniaxial compression,” *Journal of Mining and Materials Processing Institute of Japan*, vol. 108, pp. 543–548, 2018.

[3] K. Hashiba and K. Fukui, “Index of loading-rate dependency of rock strength,” *Rock Mechanics and Rock Engineering*, vol. 48, no. 2, pp. 859–865, 2015.

[4] L. Ma and J. J. K. Daemen, “Strain rate dependent strength and stress-strain characteristics of a welded tuff,” *Bulletin of Engineering Geology and the Environment*, vol. 65, no. 3, pp. 221–230, 2006.
[5] H. S. Jeong, S. S. Kang, and Y. Obara, "Influence of surrounding environments and strain rates on strength of rocks under uniaxial compression," *International Journal of the Japanese Committee for Rock Mechanics*, vol. 44, pp. 321–331, 2008.

[6] S. Khamrat and K. Fuenkajorn, "Effects of loading rate and pore pressure on compressive strength of rocks," in *Proceedings of the 11th International Conference on Mining, Materials and Petroleum Engineering*, pp. 11–13, Buffalo, NY, USA, July 2013.

[7] J. Yang, "Effect of displacement loading rate on mechanical properties of sandstone," *Electronic Journal of Geotechnical Engineering*, vol. 20, pp. 591–602, 2015.

[8] A. Aghaei Araei, H. R. Razeghi, A. Ghalandarzadeh, and S. Hashemi Tabatabaei, "Effects of loading rate and initial stress state on stress-strain behavior of rock fill materials under monotonic and cyclic loading conditions," *Scientia Iranica*, vol. 19, no. 5, pp. 1220–1235, 2012.

[9] F. Dai, K. Xia, and L. Tang, "Rate dependence of the flexural tensile strength of Laurentian granite," *International Journal of Rock Mechanics and Mining Sciences*, vol. 47, no. 3, pp. 469–475, 2010.

[10] F. Dai, K. Xia, and L. Tang, "Rate dependence of the flexural tensile strength of Laurentian granite," *International Journal of Rock Mechanics and Mining Sciences*, vol. 47, no. 3, pp. 469–475, 2010.

[11] H. Wu and D. Ma, "Fracture response and mechanisms of brittle rock with different numbers of openings under uniaxial loading," *Geomechanics and Engineering*, vol. 25, no. 6, pp. 481–493, 2021.

[12] X. Wu, "Stress relaxation, strain hardening and strain softening of rock," *Progress in Geophysics*, vol. 14, pp. 71–76, 1996.

[13] K. Fukui, S. Okubo, and Y. Nishimatsu, "Generalized relaxation behaviour of rock under uniaxial compression," *Shigen-To-Sozai*, vol. 108, no. 7, pp. 543–548, 1992.

[14] S. Okubo, K. Fukui, and X. Jiang, "Loading rate dependency of young's modulus of rock," *Shigen-To-Sozai*, vol. 117, no. 1, pp. 29–35, 2001.

[15] C. F. Chen, T. Xu, and S. H. Li, "Microcrack evolution and associated deformation and strength properties of sandstone samples subjected to various strain rates," *Minerals*, vol. 8, no. 6, pp. 1–20, 2018.

[16] X. Wu, "Stress relaxation, strain hardening and strain softening of rock," *Progress in Geophysics*, vol. 14, pp. 71–76, 1996.

[17] K. Fukui, S. Okubo, and Y. Nishimatsu, "Generalized relaxation behaviour of rock under uniaxial compression," *Shigen-To-Sozai*, vol. 108, no. 7, pp. 543–548, 1992.

[18] S. Okubo, K. Fukui, and X. Jiang, "Loading rate dependency of young's modulus of rock," *Shigen-To-Sozai*, vol. 117, no. 1, pp. 29–35, 2001.

[19] C. F. Chen, T. Xu, and S. H. Li, "Microcrack evolution and associated deformation and strength properties of sandstone samples subjected to various strain rates," *Minerals*, vol. 8, no. 6, pp. 1–20, 2018.

[20] W. R. Wawersik and C. Fairhurst, "A study of brittle rock fracture in laboratory compression experiments," *International Journal of Rock Mechanics and Mining Science & Geomechanics Abstracts*, vol. 7, no. 5, pp. 561–575, 1970.

[21] H. L. Zhang, J. Xu, and S. Okubo, "Research on loading rate dependency of rock under stress-feedback controlling," *Chinese Journal of Rock Mechanics and Engineering*, vol. 36, pp. 93–106, 2017.

[22] S. Okubo, K. Fukui, and X. Gao, "Rheological behaviour and model for porous rocks under air-dried and water-saturated conditions," *The Open Civil Engineering Journal*, vol. 2, no. 1, pp. 88–98, 2008.