ENERGY EVOLUTION AND DISTRIBUTION LAW OF ROCK UNDER THERMAL MECHANICAL COUPLING

by

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The characteristics of the energy evolution and distribution of rock during deformation and failure were studied based on thermal mechanical coupling tests completed by Min Ming at his Master's thesis in 2019. Dissipated energy is greater than elastic energy at the crack closure stage, while elastic energy is dominant at the linear elastic stage. At the post-peak failure stage, elastic energy is released rapidly before 800 °C and released slowly at 1000 °C. A comprehensive evaluation index to examine the influence of temperature on rock strength and deformation ability was proposed from the perspective of elastic energy accumulation ability. The negative effect of temperature on the strength of the rock sample is weaker than that on the elastic modulus before 400 °C. The negative effect of temperature on the strength of the rock sample is stronger than that on the elastic modulus after 600 °C.

Key words: *thermal mechanical coupling, energy evolution, energy distribution, comprehensive evaluation index of strength and deformation*

Introduction

A comprehensive understanding of rock damage and failure mechanisms under a thermal mechanical coupling environment is essential to the safe and stable development and operation of rock engineering, such as radioactive waste storage and geothermal energy utilization [1, 2]. The damage process of rock under a thermal mechanical coupling environment is an irreversible process of energy dissipation, and failure is the result of the instantaneous release of elastic energy after the rock reaches its ultimate energy storage state [3-5]. Hence, the study of energy evolution and distribution under the condition of thermal mechanical coupling can reveal the damage and failure mechanism of rock engineering and provide new insight for the study of surrounding rock stability in rock engineering.

The essence of rock damage and failure is a progressive process in which the rock gradually moves away from the initial equilibrium state and finally fails and attains a new equilibrium [6], so it is reasonable to study the deformation and failure of rock from the view-

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point of energy. Peng *et al.* [7] proposed a strength criterion and brittleness indexes based on energy release and dissipation. Meng *et al.* [8, 9] studied the effect of different loading rates on the energy evolution of sandstone. Zhang *et al.* [10, 11] studied the chaotic characteristics of energy evolution during uniaxial compression and proposed the energy criterion of rock failure and instability. These studies mainly focused on the effect of objective factors such as loading path, loading rate, and confining pressure and subjective factors such as mineral composition, structure and size on rock energy evolution. In the research of rock thermal-mechanical coupling, most scholars currently concentrate on the effect of temperature on the physical and mechanical parameters of rock, such as wave velocity, density, elastic modulus, strength, Poisson's ratio and fracture toughness, deformation and failure characteristics, microstructure, and fracture development [12-15]. However, there are few studies exploring the damage mechanism of rock under a thermal mechanical coupled environment from the perspective of energy evolution and distribution characteristics.

In this study, based on the thermal mechanical coupling test of Beishan granite carried out by Min [16], the effect of temperature on the energy evolution and distribution of rock samples was studied. The relative degree of deterioration of strength and elastic modulus of rock samples was discussed in detail *via* a comprehensive evaluation index. The results of this study are of great significance for understanding the deformation and failure mechanism of rock under a thermal mechanical coupling environment from the perspective of energy evolution.

Review of thermal mechanical coupling tests

Min [16] carried out uniaxial compression tests on Beishan granite samples with a diameter of 25 mm and height diameter ratios of 1:1, 2:1, 3:1, and 4:1. The influence of rock sample size and high temperature environment on the mechanical properties of rock was studied. Among these properties, the stress-strain curve of the thermal mechanical coupling uniaxial compression test of a standard rock sample with a height diameter ratio of 2:1 is plotted in fig. 1, and the physical and mechanical parameters related to deformation and strength are shown in tab. 1.

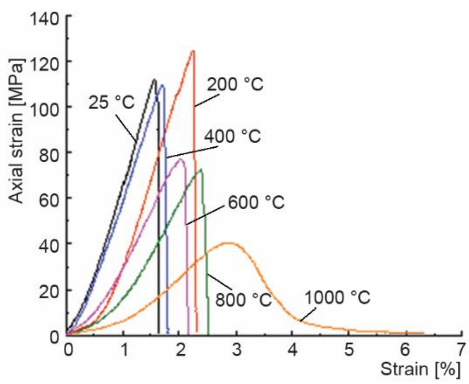

Figure 1. Stress-strain curves of rock samples under thermal mechanical coupling [16]

Table 1. Physical and mechanical parameters of rock samples under thermal mechanical coupling [16]

Temperature [°C]	Peak strength [MPa]	Peak strain [%]	Elastic modulus [GPa]
25	112.04	1.56	8.27
200	124.85	2.25	8.21
400	110.25	1.71	7.48
600	77.12	2.04	5.06
800	72.30	2.39	4.45
1000	40.77	2.88	2.24

Energy evolution and distribution law of rock sample

Strain energy calculation method

According to the First law of thermodynamics, it can be assumed that there is no heat exchange during loading. At the constant temperature stage, the energy only exists in the form of elastic energy and dissipation energy. According to the conservation of energy, the following relation exists:

$$U = U^{\mathrm{d}} + U^{\mathrm{e}} \tag{1}$$

where U is the input total energy from the external environment, U^{e} – the elastic energy accumulated inside the rock, and U^{d} – the energy dissipated by the rock during loading.

Figure 2 shows the loading and unloading stress-strain curve of rock at the stress level σ'. When loading to σ', the dissipated energy can be determined by the area between the loading curve and the unloading curve. The elastic energy, which can be determined by the area between the unloading curve and the abscissa axis. The energy calculation method is:

$$U^{\mathrm{e}} = \int_{\varepsilon'}^{\varepsilon''} \sigma' \mathrm{d}\varepsilon = \frac{\sigma'^2}{2E_0} \tag{2}$$

$$U^{\mathrm{d}} = \int_{0}^{\varepsilon''} \sigma' \mathrm{d}\varepsilon - \int_{\varepsilon'}^{\varepsilon''} \sigma' \mathrm{d}\varepsilon = \int_{0}^{\varepsilon''} \sigma' \mathrm{d}\varepsilon - \frac{\sigma'^2}{2E_0} \tag{3}$$

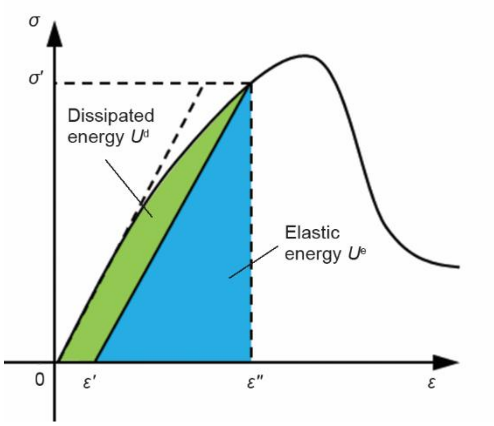

Figure 2. Schematic diagram of the calculation of elastic energy and dissipative energy

where σ' is the axial stress level, ε' – the strain value corresponding to σ', ε'' – the corresponding strain value when σ' is unloaded to 0, and E_0 – the elastic modulus.

Energy evolution of rock sample under thermal mechanical coupling

According to eqs. (1)-(3) and the stress-strain curves, the evolution law of U, U^{e}, and U^{d} during uniaxial compression of the rock sample at different temperatures can be drawn as shown in fig. 3.

– *Crack closure stage*: The growth rate of U^{e} and U^{d} of granite is small, and U is mainly used for the dissipation of continuous closure of cracks and defects in rock, so U^{d} is slightly greater than U^{e}.
– *Linear elastic stage*: The U^{e} growth rate increases gradually with axial strain, while the U^{d} growth rate is still small. The U^{d} has no significant change, and U^{e} of the rock sample is dominant at this stage.
– *Pre-peak plastic hardening stage*: After the rock sample enters the yield stage, the U^{e} growth rate slows slightly, reaching a maximum at the stress peak point. As seen from figs. 3(a)-3(e), when the temperature is below 600 °C, the pre-peak accumulation energy is 0.59--0.95 MJ/m^3, which means a relatively high energy storage level. Figure 3(f) shows that the pre-peak accumulated elasticity at 1000 °C is only 0.37 MJ/m^3, indicating that the structure

of the rock sample has changed dramatically and that much internal damage has been generated, which significantly reduces the energy storage capacity of the rock sample.

– *Post-peak failure stage*: Figsures 3(a)-3(e) shows that below 800 °C, the accumulated U^e is released rapidly, contributing to the sharp decrease in U^e. The U^d increases rapidly, indicating that below 800 °C, only a small amount of external energy input can drive the rock sample to lose its bearing capacity completely in a short period of time. Figure 3(f) shows that at 1000 °C, the pre-peak accumulated U^e of the rock sample is released slowly. This indicates that at 1000 °C, after the peak stress, the rock sample mainly experiences ductile failure. In addition, this is also related to the low pre-peak accumulated U^e of the rock sample at 1000 °C, which requires the input of a large amount of energy to drive the unstable expansion of cracks.

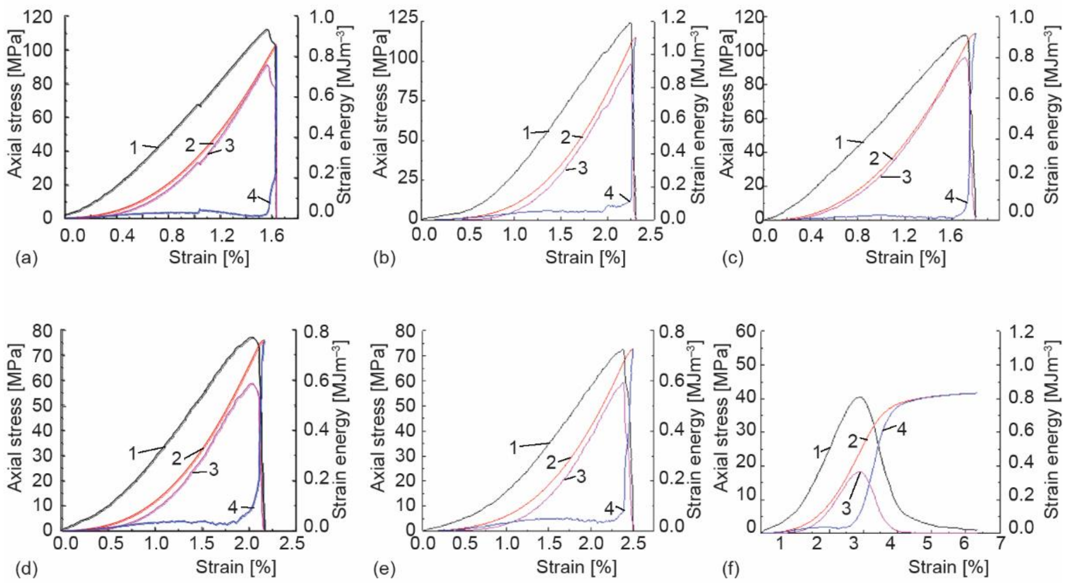

Figure 3. Energy evolution curve of the rock sample under thermal mechanical coupling; (a) 25 °C, (b) 200 °C, (c) 400 °C, (d) 600 °C, (e) 800 °C, and (f) 1000 °C: *1 – axial stress, 2 – total strain energy, 3 – elastic strain energy, 4 – dissipative strain energy*

Energy distribution of rock sample under thermal mechanical coupling

The 2-D parameters were introduced to compare the distribution of U^e and U^d in different stages:

$$K_e = \frac{U^e}{U}, \quad K_d = \frac{U^d}{U} \tag{4}$$

where K_e is the elastic energy ratio and K_d – the dissipated energy ratio.

Figure 4 shows variations of K_e and K_d with axial strain under thermal mechanical coupling. When K_e and K_d are symmetric with respect to the straight line equal to 0.5, their change trends with axial strain are opposite. After analyzing the variation characteristics of K_e, it is sufficient to understand the energy distribution mechanism of rock samples during deformation and failure.

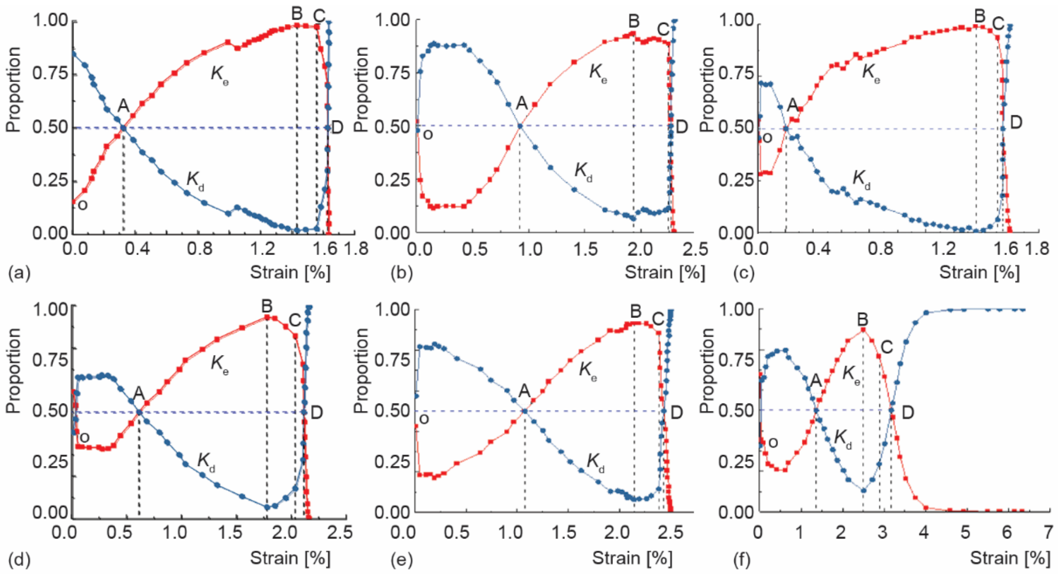

Figure 4. Variations of K_e and K_d with axial strain under thermal mechanical coupling; (a) 25 °C, (b) 200 °C, (c) 400 °C, (d) 600 °C, (e) 800 °C, and (f) 1000 °C

Section OA (crack closure stage): K_e is always less than K_d. At 25 °C, K_e increases to 0.5 (point A) with axial strain. When the temperature is above 200 °C, K_e first decreases to the minimum value with axial strain. After K_e remains at the minimum for a short time, it increases to 0.5 (point A) with the axial strain.

Section AB (elastic stage): K_e increases non-linearly with axial strain, and the growth rate is fast first and then slow. At the initial yield point (point B), the proportion of U^e reaches a maximum, and the growth rate of K_e becomes 0.

Section BC (prep-peak yield stage): K_e begins to decrease from the maximum value with axial strain. Specifically, the point of ultimate energy storage capacity (point C) does not coincide with the point of maximum K_e (point B). When the temperature is 400 °C, the decreasing trend during this stage is obvious. In the post-peak failure stage, K_e decreases to 0 with axial strain, and point D is the point where K_e is equal to K_d. Below 800 °C, K_e rapidly drops to 0, while it approaches 0 slowly at 1000 °C.

Comprehensive evaluation of the temperature effect on rock strength and deformation

The effect of temperature on rock strength (deformation capacity) can be quantitatively characterized by eq. (5). However, eq. (5) can be used to compare the effect of temperature on the strength and deformation capacity of rock. According to eq. (6), it is obvious that the ultimate energy storage capacity of the rock sample under thermal coupling is related to the strength and deformation of the rock sample. It is feasible to comprehensively evaluate the influence of temperature on rock strength and deformation from the perspective of elastic energy accumulation ability. Therefore, as shown in eq. (7), a comprehensive evaluation index to examine the influence of temperature on rock strength and deformation ability was proposed. Thus, we have:

$$K_T^\sigma = \frac{\sigma_T}{\sigma_0}\ , \quad K_T^E = \frac{E_T}{E_0} \tag{5}$$

$$U_T^{\rm e} = \frac{\sigma_T^2}{2E_T} \tag{6}$$

$$K_T^U = \frac{U_T^{\rm e}}{U_0^{\rm e}} = \frac{\sigma_T^2 E_0}{\sigma_0^2 E_T} = \frac{(K_T^\sigma)^2}{K_T^E} \tag{7}$$

where K_T^σ is the ratio of peak stress σ_T at high temperature to σ_0 at normal temperature, K_T^E – the ratio of elastic modulus E_T at high temperature to E_0 at normal temperature, and K_T^U – the ratio of ultimate energy storage capacity U_T^e at high temperature to $U_0^{\rm e}$ at normal temperature.

The reduction in strength (elastic modulus) with temperature, *i. e.*, K_T^σ, K_T^E) less than 1, was defined as a negative effect of temperature on rock strength (elastic modulus). Conversely, it is a positive effect. Generally, temperature has a negative effect on rock strength and elastic modulus. When K_T^U is equal to 1, temperature has the same effect on the strength and deformation of rock. When K_T^U is greater than 1, the negative effect of temperature on strength is stronger than that on elastic modulus. Conversely, when K_T^U is less than 1, the negative effect of temperature on rock strength is weaker than that on elastic modulus. Therefore, K_T^U can be used to comprehensively evaluate the effect of temperature on the strength and deformation capacity of rock. According to eq. (7), the K_T^U, K_T^σ, and K_T^E values of rock samples under thermal mechanical coupling are shown in fig. 5. At 200 °C, the temperature has a positive effect on the strength of the rock sample, and it has a negative effect after 400 °C. From 200 °C, the temperature always has a negative effect on the elastic modulus of rock samples. Before 400 °C, the negative effect of temperature on the strength of the rock sample is weaker than that on the elastic modulus. The K_T^U is close to 1 at 400 °C, indicating that temperature has the same effect on the strength and deformation of the rock sample. The negative effect of temperature on the strength of the rock sample is stronger than that on the elastic modulus after 600 °C.

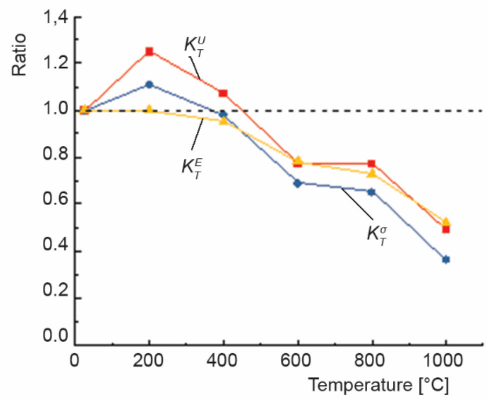

Figure 5. K_T^U, K_T^σ, **ˢand** K_T^E **values of rock samples under thermal mechanical coupling**

Conclusion

The energy evolution and distribution characteristics of rock under thermal mechanical coupling were studied. The comprehensive evaluation of the influence of temperature on rock strength and deformation was analyzed and discussed in detail. Based on the present investigation, the following conclusions are drawn. The $U^{\rm d}$ is greater than $U^{\rm e}$, and $K_{\rm e}$ is always less than 0.5 at the crack closure stage. The $U^{\rm e}$ is dominant at the linear elastic stage. The $K_{\rm e}$ non-linearity increases with axial strain and reaches its maximum at the initial yield point.

The U^d increases slowly, and K_e begins to decrease from the maximum value at the pre-peak plastic hardening stage. At the post-peak failure stage, U^e is released rapidly and U^d increases rapidly before 800 °C. The U^e is released slowly and U^d increases slowly at 1000 °C. Below 800 °C, K_e rapidly drops to 0, while it approaches 0 slowly at 1000 °C. A comprehensive evaluation index K_T^U to examine the influence of temperature on rock strength and deformation ability was proposed. The negative effect of temperature on the strength of the rock sample is weaker than that on the elastic modulus before 400 °C. K_T^U is close to 1 at 400 °C, indicating that the temperature range of the same effect on the strength and deformation of the rock sample is approximately 400 °C. The negative effect of temperature on the strength of the rock sample is stronger than that on the elastic modulus after 600 °C.

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Nomenclature

E_0 – elastic modulus at room temperature, [GPa]
E_T – elastic modulus at high temperature, [GPa]
K_d – dissipated energy ratio, [–]
K_e – elastic energy ratio, [–]
T – temperature, [°C]
U – input total energy, [MJm^{-3}]
U^d – dissipated energy, [MJm^{-3}]
U^e – elastic energy, [MJm^{-3}]

Greek symbols

ε' – strain corresponding to σ' [–]
ε'' – strain when σ' is unloaded to 0, [–]
σ' – axial stress, [Mpa]
σ_0 – peak stress at room temperature, [Mpa]
σ_T – peak stress at high temperature, [Mpa]

References

[1] Sundberg, J., *et al.*, Modelling of Thermal Rock Mass Properties at the Potential Sites of a Swedish Nuclear Waste Repository, *International Journal of Rock Mechanics and Mining Sciences*, *46* (2009), 6, pp. 1042-1054
[2] Marques, J., *et al.*, Hydrothermal Alteration of Hercynian Granites, Its Significance to The Evolution of Geothermal Systems in Granitic Rocks, *Geothermics*, *39* (2010), 2, pp. 152-160
[3] You, M. Q., *et al.*, Energy Analysis on Failure Process of Rock Specimens, *Chinese Journal of Rock Mechanics and Engineering*, *21* (2002), 6, pp. 778-781
[4] Xie, H. P., *et al.*, Energy Mechanism of Deformation and Failure of Rock Masses, *Chinese Journal of Rock Mechanics and Engineering*, *27* (2008), 9, pp. 1729-1740
[5] Steffler, E., *et al.*, Energy Partitioning for a Crack Under Remote Shear and Compression, *International Journal of Fracture*, *120* (2003), 4, pp. 563-580
[6] Xie, H. P., *et al.*, Energy Dissipation of Rock Deformation and Fracture, *Chinese Journal of Rock Mechanics and Engineering*, *23* (2004), 21, pp. 3565-3570
[7] Peng, R. D., *et al.*, Energy Dissipation and Release During Coal Failure under Conventional Triaxial Compression, *Rock Mechanics and Rock Engineering*, *48* (2015), 2, pp. 509-526
[8] Meng, Q. B., *et al.*, Research on Non-Linear Characteristics of Rock Energy Evolution under Uniaxial Cyclic Loading and Unloading Conditions, *Environmental Earth Sciences*, *78* (2019), 23, pp. 1-20
[9] Meng, Q. B., *et al.*, Effects of Acoustic Emission and Energy Evolution of Rock Specimens under The Uniaxial Cyclic Loading and Unloading Compression, *Rock Mechanics and Rock Engineering*, *49* (2016), 10, pp. 1-14
[10] Zhang, Z. Z., *et al.*, Confining Pressure Effect on Rock Energy, *Chinese Journal of Rock Mechanics and Engineering*, *34* (2015), 1, pp. 1-11
[11] Zhang, Z. Z., *et al.* Experimental Research on Energy Evolution of Red Sandstone Samples under Uniaxial Compression, *Chinese Journal of Rock Mechanics and Engineering*, *31* (2012), 5, pp. 953-962

[12] Zhang, Z. X., *et al.*, Effects of High Temperatures on Dynamic Rock Fracture, *International Journal of Rock Mechanics and Mining Sciences*, *38* (2001), 2, pp. 211-225
[13] [13] Tian, H., *et al.*, Physical Properties of Sandstones after High Temperature treatment, *Rock Mechanics and Rock Engineering*, 45 (2012), 6, pp.1113-1117
[14] Mahanta, B., *et al.*, Influence of Thermal Treatment on Mode I Fracture Toughness of Certain Indian Rocks, *Engineering Geology*, *210* (2016), 5, pp. 103-114
[15] Freire-Lista, D., *et al.*, Thermal Stress-Induced Microcracking in Building Granite, *Engineering Geology*, *206* (2016), 3, pp. 83-93
[16] Min, M., Experimental Study on High Temperature Mechanical Properties of Beishan Granite, Master's thesis, China University of Mining and Technology, Xuzhou, China, 2019

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