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Research Article

Experimental Investigation of Thermal Cracking and Permeability Evolution of Granite with Varying Initial Damage under High Temperature and Triaxial Compression

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Thermal cracking and permeability evolution of granite under high temperature and triaxial compression are the key to designing high-level waste disposal sites. In this paper, uniaxial compression tests of granite specimens with different axial compression are designed, and then a solid-head-designed coupling triaxial testing system is applied to study thermal cracking and permeability evolution of granite specimen with different damage at different inlet gas pressures (1, 2, 4, and 6 MPa) and temperatures (ranging from 100 to 650°C). The test results show that granite, nearly impermeable rocks, can show a striking increase of permeability by heating beyond the critical temperature. When the initial axial pressure is 60% or 70% of the uniaxial compressive strength, the growth of granite permeability exhibits three stages during 100~650°C heating process. Permeability increases by two orders of magnitude, but it does not reach the maximum value (i.e., a network of interconnected cracks is not fully formed in the specimen). With increasing initial damage, permeability shows a sharp increase. Permeability increases by three orders of magnitude, it is in equilibrium state, and a network of interconnected cracks is fully formed in the specimen. Permeability of granite has a critical temperature at which permeability increases sharply. When the temperature is lower than the critical temperature, the magnitude of permeability is 10^{-18} m^2 with a slight increase. When temperature is higher than the critical temperature, the magnitude of permeability is 10^{-15} m^2 with a sharp increase. The critical temperature is related to the initial damage of specimen, and the critical temperature is smaller with the initial damage going larger. Therefore, studying thermal cracking and permeability evolution of granite with different initial damage under high temperature and triaxial compression is expected to provide necessary and valuable insight into the design and construction of high-level waste disposal structures.

1. Introduction

Construction of an underground disposal for high-level nuclear waste is a complex project currently being studied by the nuclear states. The development of a nuclear waste disposal repository generally requires basic research, site selection, underground laboratory studies, and disposal library design, which is a long-term project. In recent years, China has gradually accelerated its development of nuclear power, and a large-scale nuclear waste disposal system is urgently needed. At present, a geological repository for nuclear waste is the most accepted method worldwide [1–3]. Granite is one of the most important candidate bedrock types for high-level waste disposal sites because of its low permeability, high strength, and high availability [4]. The United States has been conducting the research on granite as a nuclear waste disposal site for more than 50 years, but no conclusions have been drawn so far. A core problem is that the residual activity of the nuclear waste causes the granite to rise in temperature. Differences in thermal expansion for different mineral particles and thermal stress induced by changing temperature can lead to the expansion of micro-cracks. Cracks induced by decay heat are likely to increase the permeability of the granite, which may facilitate transport of radionuclides out of the granitic body via groundwater [5, 6]. In addition, the overlying rock, roadway excavation, increasing temperature, and groundwater alter the stress on the granitic body producing the anisotropies and fractures, thereby weakening the granite. Hence, it is of great importance to examine the evolution of thermal damage and granite permeability high temperature and high stress conditions to provide support for nuclear waste disposal sites.

High-level waste disposal is a thoroughly researched topic. Hudson et al. [7] summarized the problems of multifield coupling in high-level waste disposal and proposed that multifield coupling is crucial to high-level waste disposal. Dwivedi et al. [8] reported the thermal properties of granite in various countries' preselected nuclear disposal, which provide a reference for studying the thermal properties of granite. In addition, physical and mechanical properties, modified by thermal cracking, have been extensively investigated in laboratory tests [9–12]. Two mechanisms for thermal cracking were summarized by Yong and Wang [13]. Araúj et al. [14] examined the mechanical properties of reservoir rocks obtained in a laboratory at room temperature, characterized rock behavior under normal downhole or steam injection conditions, and found that nonnegligible variations in mechanical properties of reservoir rocks were detected from tests conducted at room temperature and at varying temperatures. Inserra et al. [15] took into account a nonlinear stress-strain relationship of the medium, provided analytical solutions for transmitted waveforms, and reproduced experimental results. Chen et al. [16] found that the cracking threshold temperature of Westerly granite is 60°C~70°C. Homand and Houpert [17] found that, in granite, thermal stress produces new fractures. Zhao et al. [18–20] carried out a systematic experimental study on thermal cracking regularity and permeability evolution of a large granite sample in the range of 20~600°C and found that thermal cracking is intermittent with two or more peak intervals and permeability also presented multiple peak accordingly.

For high-level radioactive waste repositories, a comprehensive understanding of the evolution of permeability with increasing temperature is fundamental. However, the above studies on the thermal cracking and permeability of granite mainly focus on the influence of high temperature. Few studies on thermal cracking and permeability evolution of granite with different initial damage under triaxial compression exist. In this paper, the granite from Pingyi, Shandong Province, China, is tested to simulate the real environment of a nuclear waste disposal site. Thermal cracking and permeability of the granite are studied by the self-designed solid-head-coupled triaxial rock permeability testing system. The results of this study are expected to provide a necessary and valuable reference for the design and construction of high-level waste disposal sites.

2. Experimental Work

2.1. Sample Preparation. Granite specimens are 50 mm in diameter and 100 mm long as per the International Society for Rock Mechanics guidelines. Specimens are drilled out from a single block of granite rock. A milling machine is used to flatten the ends of the samples.

2.2. Description of Experimental Rig and Measured Parameters. In order to conduct the thermal cracking and permeability of granite under high temperature and triaxial compression, the solid-head triaxial rock permeability test system self-designed by Taiyuan University of Technology, China, is adopted (Figures 1 and 2). The solid-head triaxial rock permeability test system consists of three parts, that is, a three-axis loading system, gas pressure system, and heating system. Among these, the three-axis loading system consists of an axial part and a side part. The maximum axial pressure and confining pressure can reach 100 MPa, which can simulate a high stress environment. In the experiment, the hydrostatic pressures are used to simulate a high stress environment. In order to simulate pore pressure, an aperture is created in the axial bore. The maximum pore pressure can reach up to 10 MPa. It is noted that dissolved water in granite will damage rock sample and generate some new cracks, which results in inaccuracy of permeability experiment. Nitrogen is used because of its chemical stability and lack of contamination at high temperature and pressure. Nitrogen has a certain risk under high pressure conditions, so the maximum inlet pressure in the test is 6 MPa for safety. To prevent the gas from escaping from the side direction, the inlet pressure ratio is lowered by two meters. The temperature is controlled by an electric oven line wrapped around the specimens, and insulation is used to avoid heat loss. Samples are heated at a rate of 10°C/min until the nominal temperature is reached. Not that the low rate of heating is used to eliminate the influence of other factors on the thermal cracking of granite and ensure that thermal cracking results only from the temperature effect and not thermal gradient.

To eliminate the effect of differential stress on thermal cracking, rock specimens were placed under a steady hydrostatic pressure. When permeability begins to change, the permeability test is conducted. The test is performed after the gas pressure is stabilized at 2 h, and the gas flow per pore pressure is tested at least 5 times. The steady-state gas method of Darcy [1, 21–23] method is used to test the permeability of granite specimen. The permeability can be expressed as follows:

$$k = \frac{2\mu P_0 Q_0 L}{(P_1^2 - P_2^2)A}, \quad (1)$$

where k is the gas permeability (m^2); μ is the dynamic viscosity of gas (MPa·s); P_0 is the atmospheric pressure; Q_0 is the gas flow rate ($m^3 \cdot s^{-1}$); L and A are the length and sectional area of the specimen (m, m^2); and P_1 and P_2 are the inlet gas pressure and outlet gas pressure (MPa), respectively, usually $P_2 = P_0 = 0.1$ MPa. Accordingly, the gas

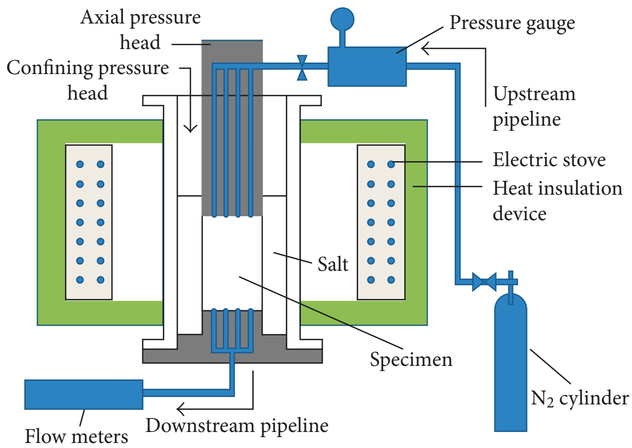


Figure 1: Illustration of the solid-head-coupled triaxial rock permeability testing system by Taiyuan University of Technology, China.

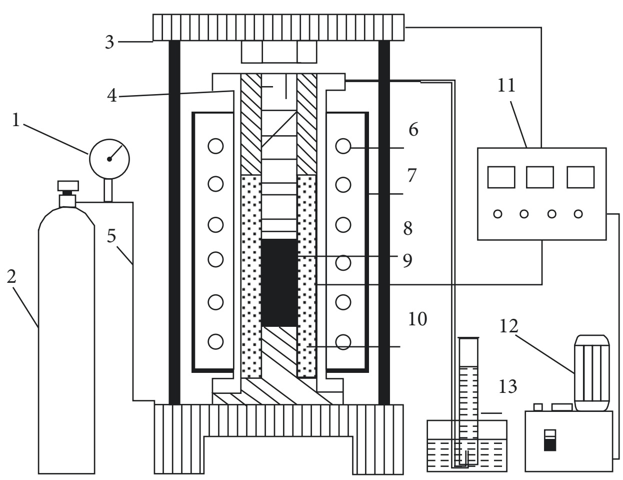


Figure 2: Schematic diagram of high-temperature triaxial permeability testing system: (1) pressure gauge, (2) nitrogen tank, (3) support frame, (4) steel tube, (5) valve, (6) heating wire, (7) muff, (8) specimen, (9) thermocouple, (10) graphite packing, (11) temperature and pressure controller, (12) oil pump, and (13) measuring equipment of gas flow.

flow rate, the inlet gas pressure, and the outlet pressure of N_2 are measured in the process of testing to calculate the permeability. The length and sectional area of the specimens were measured before the test, and the slight deformation of the specimen is ignored during the experiment.

3. Experimental Procedure and Results Analysis

3.1. Experimental Procedure. Uniaxial compression test of granite is carried out, and uniaxial compressive strength (UCS) of these granites is 160 MPa. Then, uniaxial compression experiments with initial pressures of 60% (96 MPa), 70% (112 MPa), 80% (128 MPa), and 90% (144 MPa) of UCS are designed. Finally, a solid-head designed coupled triaxial testing system is applied to study the evolution of thermal cracking and permeability of granite. The samples are heated to 100, 150, 200, 250, 300, 350, 400, 450, 500, 600, and 650°C. The confining pressure is gradually increased to 25 MPa. After the gas matrix is stabilized, the permeability of the granite specimen is measured at the initial temperature with inlet gas pressure of 1, 2, 4, and 6 MPa, respectively. The inlet gas pressure should be maintained for at least 15 minutes to collect sufficient gas and measure a steady flow at the corresponding inlet gas pressure. In order to improve the accuracy of the experimental results, each pore pressure needs to be measured at least three times. When all gaze permeability tests were completed, the specimens were heated at a rate of about 10°C/min.

3.2. Results Analysis and Discussion. The permeability of granite specimen at different inlet gas pressures and temperatures is as shown in Figure 3. When the initial damage of granite is different, the change rule of permeability is different. The evolution of permeability can be roughly divided into two patterns, that is, granite specimen with the low initial damage (when the initial axial compression is 60% or 70% of UCS) and granite specimen with the high initial damage (when the initial axial compression is 80% or 90% of UCS). In the low temperature range (from about 100 to 300°C), permeability both increases slowly with temperature in two patterns. For granite specimen with the low initial damage, the permeability reaches a maximum value at 300°C within the local temperature range. As temperature continues to increase, permeability increases, but the equilibrium value is not reached, indicating that a network of interconnected cracks is not formed in the granite. However, for granite specimen with the high initial damage, with increasing temperature, permeability increases rapidly at the critical temperature (the initial axial compression is 80% of UCS and the critical temperature is 400°C, while the initial axial compression is at 90% of UCS, the temperature is 200°C), producing a rapidly growing surface, which is similar to a vertical face. In addition, as temperature continues to increase, the permeability reaches the maximum value. Finally, a nearly horizontal balanced surface forms. In summary, the permeability of granite varies with different damage at different inlet gas pressures and temperatures. Therefore, the permeability variation of granite under high temperature and triaxial compression should be studied in detail.

3.2.1. Experimental Analysis of Permeability of Granite Specimen with Different Initial Damage. In this experiment, the maximum permeability of granite specimen under thermal cracking is defined as the peak of permeability; the permeability of granite specimen at 100°C is defined as the initial permeability; the ratio between the permeability of granite specimen at different temperatures and the initial permeability is defined as multiple proportions; and the ratio between the difference between the permeability at adjacent temperatures and the temperature difference is defined as the rate of permeability change. The permeability of samples with initial axial compression of 60% and 90% of UCS is studied (Table 1).

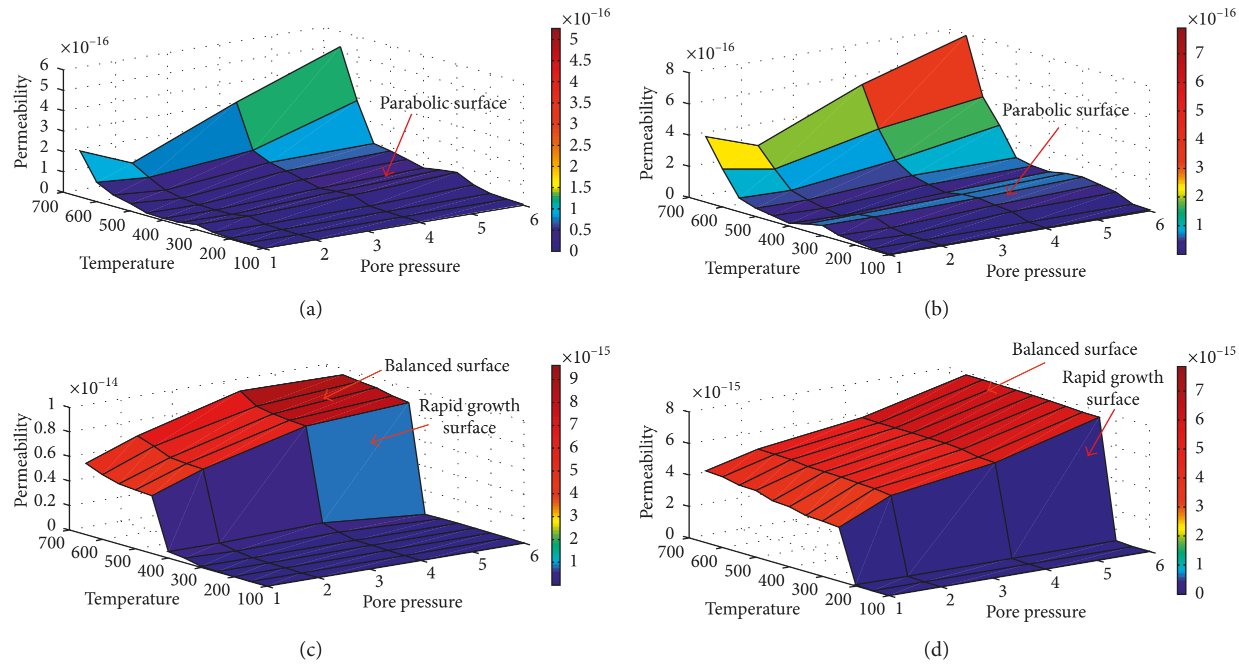


Figure 3: The permeability of granite specimen at different inlet gas pressures and temperatures. (a) The initial axial compression is 60% of UCS. (b) The initial axial compression is 70% of UCS. (c) The initial axial compression is 90% of UCS. (d) The initial axial compression is 90% of UCS.

Table 1: Permeability analysis of granite specimen with the low initial damage.

Samples	The different initial damage	Temperature (°C)	Permeability (m^2)	Multiple proportions	Rate of permeability change
		100	$4.85E-18$	1.00	—
		150	$7.35E-18$	1.52	$5.00E-20$
		200	$1.15E-17$	2.37	$8.30E-20$
		250	$3.16E-17$	6.52	$4.02E-19$
		300	$6.95E-17$	14.33	$7.58E-19$
1	60% (96 MPa)	350	$5.92E-17$	12.21	$-2.06E-19$
		400	$4.51E-17$	9.30	$-2.82E-19$
		450	$6.48E-17$	13.36	$3.94E-19$
		500	$8.35E-17$	17.22	$3.74E-19$
		550	$9.67E-17$	19.94	$2.64E-19$
		600	$2.84E-16$	58.56	$3.75E-18$
		650	$5.26E-16$	108.45	$4.84E-18$
		100	$8.72E-18$	1.00	—
		150	$5.82E-17$	6.67	$9.89E-19$
		200	$7.26E-17$	8.33	$2.88E-19$
		250	$7.61E-15$	872.71	$1.51E-16$
		300	$7.62E-15$	873.85	$2.00E-19$
2	90% (144 MP)	350	$7.69E-15$	881.88	$1.40E-18$
		400	$7.74E-15$	887.61	$1.00E-18$
		450	$7.78E-15$	892.20	$8.00E-19$
		500	$7.81E-15$	895.64	$6.00E-19$
		550	$7.82E-15$	896.79	$2.00E-19$
		600	$7.84E-15$	899.08	$4.00E-19$
		650	$7.85E-15$	900.23	$2.00E-19$

(1) The Permeability Analysis of Granite Specimen with the Low Initial Damage. A general trend observed in Figure 4 is that permeability first increases and then decreases, finally increasing rapidly as temperature increases. The variation trend of these curves is almost the same at varying inlet gas pressure. In order to simplify the analysis, take the permeability of granite specimen at an initial axial compression of 60% of UCS and inlet gas pressure at 6 MPa as an example. At the beginning of thermal cracking, the effect of thermal cracking is not large causing the permeability of samples to

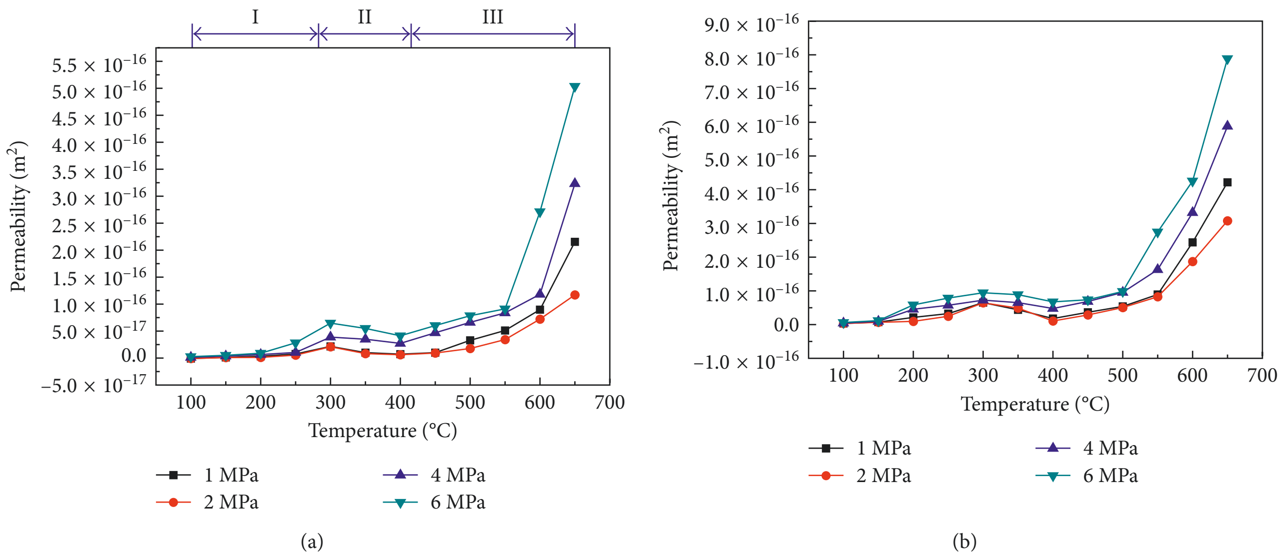


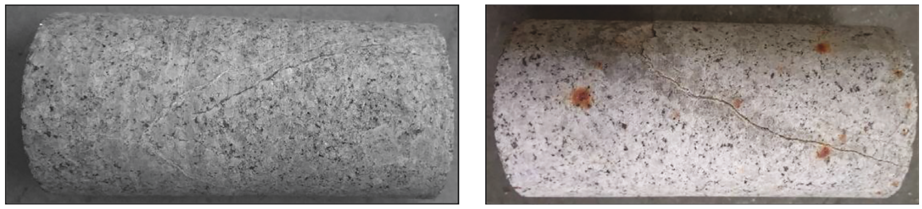
Figure 4: The permeability variation of granite specimen with the low initial damage. (a) The permeability of granite specimen when the initial axial compression is 60% of UCS. (b) The permeability of granite specimen when the initial axial compression is 70% of UCS.

show a weak variation. When the temperature reaches a certain value, the effect of thermal cracking is much more pronounced and samples experience a sharp increase in permeability. This temperature is defined as the critical temperature. The critical temperature of granite specimen at an initial axial compression of 60% of UCS is 550°C. Thus, permeability curves are divided into three phases. Here, we analyze the change in permeability at each of the three stages specifically.

Stage I (100~300°C): a slight increase in permeability of granite specimen can be seen with temperature increasing from 100 to 300°C (Figure 4). The multiple proportions is 14.33 at 300°C (Table 1), indicating that thermal cracking leads to the changes in the structure of the granite specimen (i.e., generation of new cracks or extension of the existing cracks). The results are consistent with previous research [20, 21, 24, 25]. However, the fracture rate is greater than that of Zhang et al. [24], reflecting the effect of initial damage on thermal cracking. When the temperature is approximately 300°C, the permeability reaches the peak of its curve, showing that the pore structure of the granite sample changes greatly at this time, producing more small cracks and some larger cracks. At this stage, the sample primarily undergoes elastic deformation. The following is a detailed explanation of the permeability changes in this stage. (1) The main components of granite are quartz, feldspar, calcite, illite, siderite, biotite, and muscovite. The thermal expansion coefficient for each mineral is different. With increasing temperature, the minerals expand constantly. However, the jelly connects all kinds of matter to prevent it from expanding freely, which lead to thermal stress between mineral particles. Therefore, the higher the temperature is, the greater the thermal stress, and the larger the deformation is. (2) The thermal stress is larger than ultimate strength of the granite when the temperature reaches a certain value. Fractures form inside the sample and causing the permeability of the sample to increase with increasing temperature. In conclusion, these factors lead to a slight increase in permeability of granite with increasing temperature.

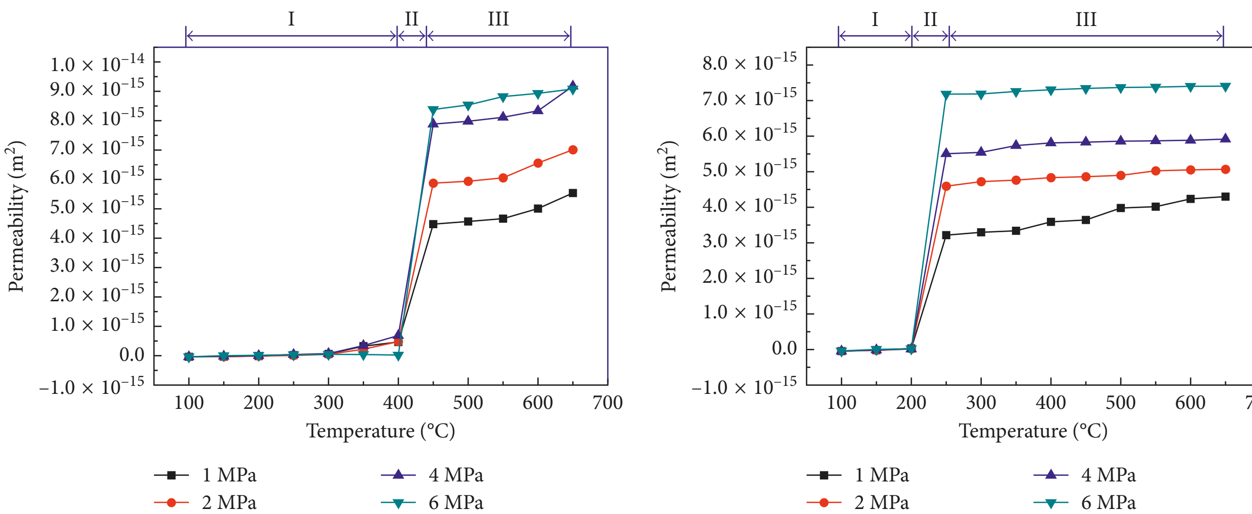
Stage II (300~550°C): according to the first stage permeability variation rule, the permeability should increase with increasing temperature. However, the results of this experiment are contrary. Why is the permeability variation of granite so abnormal in this stage? With increasing temperature, the amount of deformation of the rock should increase, forming more fractures and increasing permeability. However, the expansion deformation (i.e., recoverable elastic deformation) of the granite specimen due to thermal expansion is constrained by the high axial and confining pressure, although thermal expansion of the specimen increases with temperature, eventually leading to the closure of primary cracks and microcracks. Deformation in the first stage is mainly elastic deformation. Hence, the permeability of granite decreases. The results of this experiment are consistent with the granite experiment [20] and gypsum experiment [22].

Stage III (550~650°C): a rapid increase in granite permeability can be seen with the rise of temperature from 550 to 650°C. The permeability increases from $9.67E-17$ to $5.26E-16\,\mathrm{m}^2$, and the multiple proportion of granite permeability at 650°C is 108.45 (Table 1). The permeability of granite increases by 2 orders of magnitude compared with the permeability at 100°C, indicating that the severe thermal cracking has occurred in this stage (Figure 5). Large cracks are the main reasons for the rapid growth of the permeability in this stage. However, from the perspective of the permeability change rule, sample permeability has not reached the maximum value, which indicates that permeability will continue to grow with increasing temperature, and these cracks are not yet fully connected. The following is an explanation of the permeability changes in this stage in detail. With increasing temperature, the expansion deformation (i.e., recoverable elastic deformation) of the



(a) (b)

FIGURE 5: Thermal cracking diagram of granite specimens with the low initial damage. (a) Initial axial compression is 60% of UCS. (b) Initial axial compression is 70% of UCS.



(a) (b)

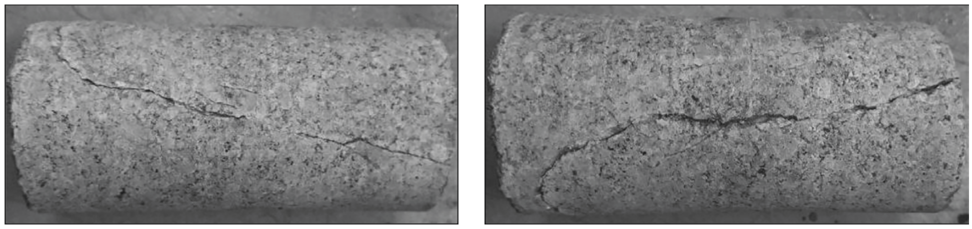
FIGURE 6: The permeability variation rule of granite specimen with the high initial damage. (a) The permeability of granite specimen with initial axial compression at 80% of UCS. (b) The permeability of granite specimen with initial axial compression at 90% of UCS.

granite specimen caused by thermal expansion becomes more obvious, which leads to the formation of cracks and macrocracks. A network of interconnected fractures is formed in some areas of granite, causing the permeability of granite specimen to increase rapidly.

(2) Permeability Analysis of Granite Specimen with the Low Initial Damage. When the initial axial compression is 80% or 90% of UCS, the permeability variation rule of granite specimen is different from that of the low damage stage (Figure 6). A general trend is that the permeability first increases and then increases rapidly with increasing temperature, showing an “s” shape tendency. The variational trend of these curves is almost the same at varying pore pressure. Compared with the permeability change rule of granite specimen with the low initial damage at the same temperature, the permeability is larger. In addition, with increasing temperature, cracks in the granite specimen are fully connected, which is caused by thermal expansion, and the permeability of granite increases by 3 orders of magnitude compared with the permeability at 100°C. In order to simplify the analysis, consider the permeability of a granite sample at 90% of UCS and a pore pressure of 6 MPa as an example. The curve of the granite sample can be divided into three thermal cracking stages, that is, the preliminary stage, severe thermal cracking, and steady thermal cracking stage.

Stage I, preliminary thermal cracking stage (100~200°C): the change rule for the permeability stage is similar to that of the low initial damage, but the permeability of the granite is greater at the same temperature. An increase in permeability of granite specimen can be seen with temperature increasing from 100°C to 200°C. The permeability increases from $8.72E-18\,\mathrm{m}^2$ to $7.26E-17\,\mathrm{m}^2$, and the multiple proportion of granite permeability at 200°C is 8.33, indicating that thermal cracking is much more pronounced than in the low initial damage at same temperature. In addition, the expansion deformation caused by thermal stress is relatively large. Hence, the permeability of granite sample increases as the temperature increases.

Stage II, severe thermal cracking (200~250°C): the stage is very different from that of low damage stage and the previous studies [20, 21]. A severe increase in granite permeability can be seen with increasing temperature. The permeability increases from $7.26E-17$ to $7.61E-15\,\mathrm{m}^2$, and the rate of permeability change reaches $1.50748E-16$, and the multiple proportion of granite permeability at 250°C is 872.71. This indicates that significant changes have taken



(a) (b)

Figure 7: Thermal cracking diagram of granite specimens with the high initial damage. (a) Initial axial compression is 80% of UCS. (b) Initial axial compression is 90% of UCS.

place in the granite structure, that is, the cracks in the granite specimen are fully connected. Why does the severe thermal cracking of thermal occur in such a short time (i.e., 200~250°C)? This is because when the initial axial compression is 90% of UCS, the granite structure has been damaged to some extent from the permeability. In addition, the secondary action of thermal stress leads to significant swelling and deformation of the granite structure under high temperature and triaxial compression. Thus, granite structural changes produce a large amount of large cracks (Figure 7), and with increasing temperature, the cracks become interconnected completing a fracture network. The granitic structure undergoes a qualitative transformation at this time, that is, the internal structure suffers serious damage, and eventually, the granite is completely destroyed. The permeability of granite experiences a significant increase, and the rate of permeability change is high.

Stage III, steady thermal cracking stage (250~650°C): the permeability is almost constant in this stage, which indicates that the cracks in the samples are fully connected. When the temperature reaches 250°C, the granite sample has been completely destroyed. The structure undergoes a qualitative transformation, and the completed fracture network has formed. In addition, the permeability of rock, that is, the ability of fluid to pass through the porous medium of the rock body, is the physical and chemical basis for accomplishing the technological process of linkage. When pore fluid is single liquid phase, the measured permeability is the absolute permeability, which is an intrinsic property of the rock which depends upon the pore structure of the granite and the applied stress [26]. Therefore, the pore structure of the granite shows little change. In summary, when the granite sample has been completely destroyed, the temperature has little effect on the pore structure, therefore, the permeability changes little.

3.2.2. Analysis of Critical Temperature. The internal crack of the rock increases continuously with increasing temperature. When a crack is connected to a network, the overall permeability of the rock will increase suddenly. Therefore, the critical temperature of the permeability of the granite exists. When the temperature is lower than the critical temperature, the permeability of a granite sample is small with a low rate of change. When the temperature is higher than the critical temperature, the permeability increases drastically. The critical temperature is also the demarcation point between the elastic-plastic deformation stage and the plastic deformation stage. Chen et al. studied the thermal cracking of carbonate and granite and found that when the temperature of carbonate is approximately 110–120°C [27], the permeability of the rock sample will increase 8~10 times. Due to the limitations of the experimental equipment, the critical temperature of the granite has not yet been discovered. In addition, granite specimens with amounts of fracture damage also have a significant relationship with the critical temperature of permeability. The original structure of the pores varies of different amounts of initial damage. In the thermal cracking process, thermal stress plays a second role on the basis of initial damage, which leads to further initiation, expansion, and penetration of microcracks. Finally, the penetration of microcracks forms a passage for material transport, that is, the overall permeability of the rock will have a sudden increase.

Critical temperature as a function of initial damage can be seen in Figure 8. The critical temperature is not linear with initial damage, and it is roughly a parabola according to the best-fit curve. The critical temperature decreases sharply as initial damage increases. When the initial axial compression is 90% of UCS, the critical temperature is 200°C, which explains the importance of the initial degree of damage to the critical temperature. The initial damage has largely destroyed the granite specimens and produced an inrecoverable plastic deformation. With increasing initial damage, the plastic deformation is greater, which leads to the formation of more cracks and completed cracks network. Intragranular thermal stress is induced by shrinkage and decomposition of minerals under high temperature and triaxial compression, which is similar to the mechanism of high confining pressure [8]. The reason for this phenomenon is contribution of intragranular thermal stresses from anisotropic expansion [1]. When the initial damage increases, the stress exceeds the local rock strength, and microcracks are generated. This indicates that intergranular thermal stresses play a decisive role in thermal cracking, and the critical temperature is dependent on the initial damage.

4. Conclusions

Uniaxial compression tests of granite specimens with different axial compression are designed, and then a solid-head coupling triaxial testing system is applied to examine the thermal cracking and permeability evolution of granite

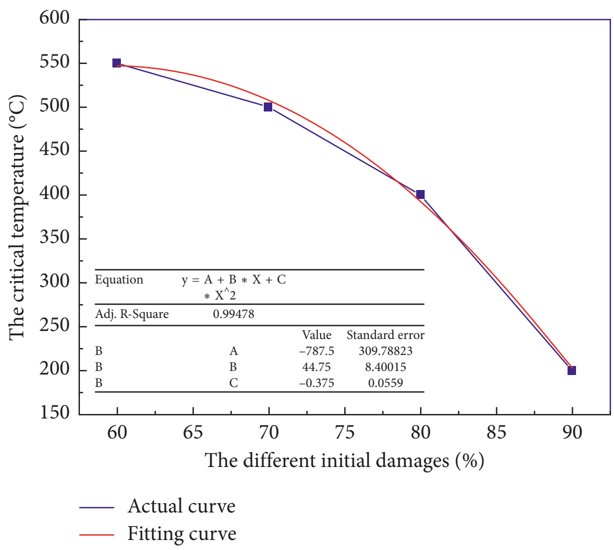


FIGURE 8: Critical temperature as a function of initial damage.

specimen with different initial damage at different intlel gas pressures (1, 2, 4, and 6 MPa) and temperatures (from 100 to 650°C). Based on the above discussion, the following conclusions are drawn:

(1) Granite, nearly impermeable rocks, can show a striking increase of permeability from heating beyond the critical temperature. With increasing temperature, the permeability can even increase by 3 orders of magnitude.

(2) The initial damage of granite specimen has a significant effect on the permeability of granite. The evolution of permeability can be roughly divided into the granite specimen with the low initial damage (when the initial axial compression is 60% or 70% of UCS) and granite specimen with the high initial damage (when the initial axial compression is 80% or 90% of UCS).

(3) When granite specimen with the low initial damage, the permeability first increases, then decreases, and finally increases rapidly with increasing temperature. The variation trend of these curves is almost the same at varying pore pressure. With increasing temperature, changes in pore structure are mainly caused by elastic deformation and plastic deformation. In particular, the decrease in permeability in the second stage indicates that some cracks are compacted, and the mutual transformation of elastic and plastic deformation is carried out in the process of thermal cracking.

(4) When granite specimen with the high initial damage, the permeability change rule is significantly different from that of granite specimen with the low initial damage. The second stage of granite specimen with the low initial damage disappears, which indicates that the initial damage has a great effect on permeability. This is because the structure of granite has some initial damage, and the secondary action of thermal stress induced by increasing temperature leads to serious swelling and deformation of the granite structure under high temperature and triaxial compression.

(5) Thermal stresses play a decisive role in thermal cracking, and the critical temperature is dependent on the initial damage. The critical temperature is not linear with initial damage. Critical temperature decreases sharply as initial damage increases.

Therefore, studying thermal cracking, permeability evolution of granite with different damage levels under high temperature, and triaxial compression is expected to provide a necessary and valuable insight into the design and construction of high-level waste disposal structures.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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References

[1] S. Chen, C. Yang, and G. Wang, "Evolution of thermal damage and permeability of Beishan granite," *Applied Thermal Engineering*, vol. 110, pp. 1533–1542, 2017.

[2] Chinese Underground Waste Disposal Committee of Chinese Society of Rock Mechanics and Engineering, *Inaugural Conference of Chinese Underground Waste Disposal Committee of Chinese Society of Rock Mechanics and Engineering and the First Academic Exchange Conference*, Beijing, China, 2006.

[3] J. Wang, W. Chen, R. Su et al., "Geological disposal of high-level radioactive waste and its key scientific issues," *Chinese Journal of Rock Mechanics and Engineering*, vol. 25, no. 4, pp. 801–812, 2006.

[4] X. H. Han, Z. H. Chu, and Y. Z. Zhang, "Thermal-induced rock cracking and its significance in engineering," *Petroleum Geology and Experiment*, vol. 27, no. 1, pp. 98–100, 2005.

[5] Y. F. Chen, S. H. Hu, K. Wei et al., "Experimental characterization and micromechanical modeling of damage-induced permeability variation in Beishan granite," *International Journal of Rock Mechanics and Mining Sciences*, vol. 71, pp. 64–76, 2014.

[6] M. Souley, F. Homand, S. Pepa, and D. Hoxha, "Damage-induced permeability changes in granite: a case example at the URL in Canada," *International Journal of Rock Mechanics and Mining Sciences*, vol. 38, no. 2, pp. 297–310, 2001.

[7] J. A. Hudson, O. Stephansson, J. Andersson et al., "Coupled T–H–M issues relating to radioactive waste repository design and performance," *International Journal of Rock Mechanics and Mining Sciences*, vol. 38, no. 1, pp. 143–161, 2001.

[8] R. D. Dwivedi, R. K. Goel, VV. R. Prasad et al., "Thermo-mechanical properties of Indian and other granites," *International Journal of Rock Mechanics and Mining Sciences*, vol. 45, no. 3, pp. 303–315, 2008.

[9] J. Lima and A. B. Paraguassú, "Linear thermal expansion of granitic rocks: influence of apparent porosity, grain size and quartz content," *Bulletin of Engineering Geology & the Environment*, vol. 63, no. 3, pp. 215–220, 2004.
[10] Y. Mahmutoglu, "Mechanical behaviour of cyclically heated fine grained rock," *Rock Mechanics and Rock Engineering*, vol. 31, no. 3, pp. 169–179, 1998.
[11] R. Tiskatine, A. Eddemani, L. Gourdo et al., "Experimental evaluation of thermo-mechanical performances of candidate rocks for use in high temperature thermal storage," *Applied Energy*, vol. 171, pp. 243–255, 2016.
[12] S. Liu and J. Xu, "An experimental study on the physico-mechanical properties of two post-high-temperature rocks," *Engineering Geology*, vol. 185, pp. 63–70, 2015.
[13] C. Yong and C. Y. Wang, "Thermally induced acoustic emission in Westerly granite," *Geophysical Research Letters*, vol. 7, no. 12, pp. 1089–1092, 1980.
[14] R. G. Araújo, J. L. Sousa, and M. Bloch, "Experimental investigation on the influence of temperature on the mechanical properties of reservoir rocks," *International Journal of Rock Mechanics and Mining Sciences*, vol. 34, no. 3-4, pp. 298.e1–298.e16, 1997.
[15] C. Inserra, S. Biwa, and Y. Chen, "Influence of thermal damage on linear and nonlinear acoustic properties of granite," *International Journal of Rock Mechanics and Mining Sciences*, vol. 62, pp. 96–104, 2013.
[16] Y. Chen, X. Wu, and F. Zhang, "Experimental research of rock thermal cracking," *Chinese Science Bulletin*, vol. 44, no. 17, pp. 1610–1612, 1999.
[17] E. F. Homand and R. Houpert, "Thermally induced microcracking in granites: characterization and analysis," *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts*, vol. 26, no. 2, pp. 125–134, 1989.
[18] Y. Zhao, Z. Wan, Y. Zhang et al., "Experimental study of related laws of rock thermal cracking and permeability," *Chinese Journal of Rock Mechanics and Engineering*, vol. 29, no. 10, pp. 1970–1976, 2010.
[19] Y. Zhao, Q. Meng, T. Kang et al., "Micro-CT experimental technology and meso-investigation on thermal fracturing characteristics of granite," *Chinese Journal of Rock Mechanics and Engineering*, vol. 1, p. 5, 2008.
[20] Y. Zhao, Z. Feng, Y. Zhao et al., "Experimental investigation on thermal cracking, permeability under HTHP and application for geothermal mining of HDR," *Energy*, vol. 132, pp. 305–314, 2017.
[21] S. Chaki, M. Takarli, and W. P. Agbodjan, "Influence of thermal damage on physical properties of a granite rock: porosity, permeability and ultrasonic wave evolutions," *Construction and Building Materials*, vol. 22, no. 7, pp. 1456–1461, 2008.
[22] T. Meng, Y. C. You, J. Chen et al., "Investigation on the permeability evolution of gypsum interlayer under high temperature and triaxial pressure," *Rock Mechanics and Rock Engineering*, vol. 50, no. 8, pp. 2059–2069, 2017.
[23] D. Jsainge, P. G. Ranjith, and S. K. Choi, "Effects of effective stress changes on permeability of Latrobe Valleybrown coal," *Fuel*, vol. 90, no. 3, pp. 1292–1300, 2011.
[24] N. Zhang, Y. Zhao, Z. Wan et al., "Experimental research on seepage laws of granite under thermal cracking action with 3d stress," *Chinese Journal of Rock Mechanics & Engineering*, vol. 29, no. 1, pp. 118–123, 2010.
[25] J. Rutqvist, B. Freifeld, K. B. Min et al., "Analysis of thermally induced changes in crackd rock permeability during 8 years of heating and cooling at the yucca mountain drift scale test," *International Journal of Rock Mechanics & Mining Sciences*, vol. 45, no. 8, pp. 1373–1389, 2008.
[26] S. Liu, S. Zhang, F. Chen et al., "Variation of coal permeability under dehydrating and heating: a case study of ulanqab lignite for underground coal gasification," *Energy & Fuels*, vol. 28, no. 11, pp. 6869–6876, 2014.
[27] Y. Chen, X. D. Wu, and F. Q. Zhang, "Experimental study on thermal cracking of rock," *Chinese Science Bulletin*, vol. 44, no. 17, pp. 1610–1612, 1999.