Research Article

Chenchen Xu, Qiang Sun, Xiaohua Pan*, Weiqiang Zhang, and Yanbing Wang

Variation on thermal damage rate of granite specimen with thermal cycle treatment

<https://doi.org/10.1515/htmp-2019-0046>

Received Feb 27, 2019; accepted Jul 24, 2019

Abstract: Temperature significantly affects the physical and mechanical properties of granite. To have a comprehensive understanding of the thermal cycle effect on uniaxial compressive strength (*UCS*) and thermal damage rate, a series of thermal cycle experiments on granite specimens were carried out with five types of designed temperatures and five types of cycle number of thermal treatments. The experimental results indicate that *UCS* decreases and thermal damage rate increases as temperature and thermal cycle increase. *UCS* of specimens cooled in water condition after thermal damage treatment are lower than those cooled in air condition. In addition, two new phenomena related to thermal damage rate were observed. Firstly, previous studies have shown that a rapid value reduction of *UCS* of specimens with one thermal cycle treatment under air cooling condition can be observed at 400°C. While the temperature threshold for the specimens treated with more than one thermal cycle under water cooling condition increases to 550°C. Secondly, a thoroughly antipodal evolution law of the thermal damage rate for the specimens with multiple thermal cycle treatments is also observed as compared to those treated by only one thermal cycle. These differences might be induced by the different microcrack initial time and their development speed. The new findings are important to understand the failure mechanism and variation process of physical and mechanical properties of granite specimens subjected to thermal cycles.

Keywords: Granite, Thermal cycle, Physical and mechanical properties

*Corresponding Author: Xiaohua Pan: School of Earth Science and Engineering, Nanjing University, Nanjing, Jiangsu Province 210023, China; Email: xhpan@ntu.edu.cn

Chenchen Xu: Geological Research Institute for Coal Green Mining, Xi'an University of Science and Technology, Xi'an 710054, China; College of Geology and Environment, Xi'an University of Science and Technology, Xi'an 710054, China

Qiang Sun: Geological Research Institute for Coal Green Mining, Xi'an University of Science and Technology, Xi'an 710054, China

1 Introduction

Granite is a type of rock widely used for constructions (*i.e.*, buildings, tunnels, bridges, etc.) owing to its good physical and mechanical properties, such as high uniaxial compressive strength (*UCS*) and modulus of elasticity [1]. However, during the life cycle, it is inevitable to encounter sudden external environmental factors which will reduce the physical and mechanical properties. Temperature is one of such key factors. Great changes in temperature, especially subjected to high temperature, different thermal expansion of different granite components will lead to a creation of inter-granular compressive and tensile forces. Once these thermal stresses exceed the strength, the original cracks propagate and new cracks initiate [2, 3]. Consequently, rapid degradations of the physical and mechanical properties of the granite occur [4–6], which results in reducing the service life in constructions or affecting the stability of the constructions. It is therefore important to have a comprehensive understanding of the thermal effect on physical and mechanical properties of the granite.

Extensive laboratory studies have been carried out to investigate the thermal effect on physical and mechanical properties of granite [7–9]. Jansen *et al.* [10] studied the thermal induced microcracks of Lac du Bonnet granite using ultrasonic imaging and acoustic emission monitoring. Chaki *et al.* [11] evaluated the influence of thermal damage on porosity, permeability and ultrasonic wave evolutions. Shao *et al.* [12] investigated the cool rate effect on physical and mechanical properties of granite. Chen *et al.* [13] assessed the thermal heating rate effect on physical and mechanical properties of Beishan granite. A series of uniaxial compression tests were carried out by Yang *et al.* [14] to evaluate the effect of high temperature treatments (200, 300, 400, 500, 600, 700 and 800°C) on the crack damage, strength and deformation failure behavior of a type of granite. Hu *et al.* [15] studied the variation

Weiqiang Zhang: School of Resources and Geosciences, China University of Mining and Technology, Xuzhou 221116, China

Yanbing Wang: State Grid Economic and Technological Research Institute CO., LTD., Beijing 102209, China

Table 1: Mineral composition and physical properties of granite specimens that were tested

Mineral composition of specimens				Moisture content (%)	density (g/cm ³)
Feldspar (%)	Quartz (%)	Amphibole (%)	Mica (%)		
35	40	20	5	0.31	2.97

of compressive strength, elastic modulus, tensile strength, and fracture toughness of granite after high-temperature treatment. Fan *et al.* [16] presented an investigation of thermal effect on micro-properties of granite through X-ray CT technique. These studies were all based on one time thermal treatment in term of heating the specimens to a designed temperature with a specific heating rate.

Tiskatine *et al.* [17] performed a series of thermal cycle experiments on two granite specimens. The charge cycle was carried out in an oven for one hour at 650°C with a heating rate of 25°C/min, and a discharge cycle was carried out in ambient air for thirty minutes at 20°C with a cooling rate of 20°C/min. The grain specimens disintegrated into small pieces after only ten thermal cycles. This study indicates that thermal cycle significantly affects the microcracks and physical and mechanical properties. So far, corresponding studies are rarely reported and comprehensive understanding of the thermal cycle effect on granite physical and mechanical properties are still insufficient. However, it is important for us to have an accuracy stability assessment of the buildings or projects constructed by granite subjected to several time fires or to several cycles of high temperatures in a fire.

In this study, a series of thermal cycle experiments on 93 granite specimens were carried out with five designed temperatures and five thermal cycles as well as related uniaxial compression tests were conducted for aforementioned aim. Based on the experimental results, the relationships among the *UCS*, the elevated temperature and thermal cycles were analyzed. What's more, to better evaluate the degree of the degeneration of the *UCS* induced by the thermal damage, a thermal damage index, $D_{\sigma c}$, was defined. The temperature and thermal cycle effects on $D_{\sigma c}$ and the rate of $D_{\sigma c}$ changes were also discussed.

2 Specimen preparation and laboratory test

2.1 Specimen preparation

The granite specimens to be tested were cored from a granite block which was collected from Zhangzhou, Fujian

Figure 1: MTS816 servo-controlled rock mechanics experimental system

Province, China. The mineral composition and physical properties of the granite are presented in Table 1. Triplicate specimens were prepared for each group test in standard size recommended by International Society for Rock Mechanics standards [18]. The diameter was 50 mm and length was 100 mm. The end surfaces were flat with an accuracy of 0.02 mm.

2.2 Thermal cycle treatment

The charge cycle was carried out in a furnace (type CYM-100) to reach a designed temperature with a heating rate of 10°C/min, and a discharge cycle was carried out in water to have a quick cooling down to the water temperature (20°C). In order to investigate the temperature and cy-

Table 2: Mean values of UCS and thermal damage index of specimens

Temperature (°C)	Uniaxial compressive strength UCS_T (MPa)						Thermal damage index (D_{sc})					
	Treatment times of thermal cycles						Treatment times of thermal cycles					
	Air cooling (AG)			Water cooling			Air cooling (AG)			Water cooling		
	1	1	5	10	15	20	1	1	5	10	15	20
25	125 (UCS_0)	-	-	-	-	-	0	-	-	-	-	-
250	110	107	90	66	58	40	0.120	0.144	0.280	0.472	0.536	0.680
350	107	90	68	53	47	36	0.144	0.280	0.456	0.576	0.624	0.712
450	77	68	61	50	50	35	0.384	0.456	0.512	0.600	0.600	0.720
550	59	59	50	41	43	37	0.528	0.528	0.600	0.672	0.658	0.704
650	46	36	29	26	25	15	0.632	0.712	0.768	0.792	0.800	0.880

cle effects, five types of designed temperatures including 250°C, 350°C, 450°C, 550°C and 650°C and five types of cycle number of thermal treatments (i.e., 1, 5, 10, 15 and 20 times) were designed. As shown in Table 2, five group tests for each temperature were conducted with different thermal cycles, such as for 250°C, thermal treatment were carried out by 1, 5, 10, 15 and 20 times. Therefore, a total of 25 group tests for water cooling condition were carried out. Simultaneously, for comparison, 5 group tests under air cooling (AG) condition (cooled in air to room temperature at 25°C) were also conducted with one time thermal treatment (250°C, 350°C, 450°C, 550°C and 650°C). What's more, 1 group of specimens were set to measure the original UCS (UCS_0) of the granite without thermal treatment at room temperature (25°C). In other words, totally 31 group tests were carried out. Each group test was repeated three times based on the prepared triplicate specimens.

2.3 Uniaxial compression test

Uniaxial compression test was conducted on an MTS816 servo-controlled rock mechanics experimental system (as shown in Figure 1). Prior to the application of a constant axial strain loading rate ($1.0 \times 10^{-5}/s$), silicon grease was greased to the top and bottom surface of the specimen to mitigate the end friction effect between the specimen and testing machine.

3 Results

The mean UCS of each group test and the thermal damage index, D_{sc} , which was defined to evaluate the degree of the degeneration of the UCS induced by the thermal damage were shown in Table 2. UCS of each test was directly

obtained from the stress-strain curve. Mean UCS were calculated based on the UCS values of each group. D_{sc} can be calculated using Eq. (1) corresponding to a ratio of mean UCS after thermal treatment (UCS_T) to the mean original UCS (UCS_0) of each group.

$$D_{sc} = 1 - UCS_T/UCS_0 \quad (1)$$

Table 2 shows that the mean value of UCS_0 is 125MPa. It can be found in Figure 2a that for specimens treated with the same thermal cycles, UCS decreases while D_{sc} increases as temperature increases. Especially between 550 and 650°C, there is a significant reduction of UCS of specimens cooled in water, i.e., the UCS of specimen with one thermal cycle decreases from 59 to 39 MPa (corresponding D_{sc} increases from 0.528 to 0.712, see the black line with square). The comparison between the specimens (1 thermal cycle) cooled in air (AG) (marked with gray line with rhombus) and cooled in water (marked with black line with square) indicates that the cooling type does not affect the UCS of the specimens at 250°C much, while it affects the UCS more significantly as the temperatures increase to 350°C and 450°C, the UCS of specimens cooled in water are smaller than those cooled in air. The same phenomenon also can be observed at 650°C. It might be due to more microcracks were formed by cooling in water at those temperatures. Figure 2b indicates that thermal cycle significantly affects the UCS , UCS decreases as the thermal cycle increases, especially at low temperature. One possible reason is that when the specimens are subjected to low temperatures, very few microcracks are formed inducing a small D_{sc} (see Figure 2b). The specimens thus have a high original UCS (one thermal cycle). The increment of the thermal cycles forms more microcracks and reduces the UCS significantly with a greater acceleration of the increment of D_{sc} . While for the specimens are subjected to high temperature, much more microcracks are formed at the first

(a)

(b)

Figure 2: UCS (solid line) and thermal damage index, D_{sc} , (dotted line) versus (a) elevated temperature, and (b) thermal cycles

thermal cycle resulting in small original UCS. It is difficult to quickly form more microcracks in the following thermal cycles. Therefore, the reduction rate of UCS in high temperature is smaller.

4 Discussions

It can be observed from Figure 2a that the temperature thresholds of having a rapid value reduction of UCS of specimens under different cooling conditions are different. In order to improve the reliability of the observed phenomenon, some test results of UCS of specimens subjected to various temperatures and cooled in AG condition from previous studies [2, 19–23] are shown in Figure 3a with the same type test results obtained from this study. These results indicate that the UCS of granite specimens cooled in AG condition have a rapid reduction at 400°C which is

(a)

(b)

Figure 3: (a) UCS (solid line) and linear expansion, α , (dotted line), and (b) thermal damage index, D_{sc} , (solid line) and α (dotted line), of granite versus elevated temperature

lower than those cooled in water condition. The acceleration of the value of the D_{sc} also can be observed at the same temperature in Figure 3b. The studies of Etienne and Poupert [24], Nasseri et al. [25, 26], Chaki et al. [11], Chen et al. [22] and Inserra et al. [27] suggested that the rapid reduction of UCS at 400°C is primarily due to the microcrack initiates at such a temperature and results in an acceleration of linear expansion α (a ratio of increment in specimen length direction to the specimen length, see the red and brown dotted lines in Figures 3a and 3b). However, in this study, the temperature threshold of significant reduction of UCS of granite specimens cooled in water condition delays to 550°C, especially in specimens with large thermal cycles (see Figure 2a). This phenomenon might be caused by that microcracks initiated earlier after specimens were treated by larger thermal cycles and cooled in water which results in having a low UCS at low temperature (i.e., the UCS at 250°C is 36 MPa after 20 thermal cycles). As temper-

(a)

(b)

Figure 4: (a) rate of thermal damage index (D_{sc}) change related to temperature, dD_{scT} , (solid line) and D_{sc} (dotted line) versus temperatures, and (b) another type of rate of thermal damage index change related to thermal cycles, $d\log D_{scN}$, (solid line) and $\log D_{sc}$ (dotted line), versus cycles

Figure 5: Rate of thermal damage index (D_{sc}) change related to temperature, dD_{scT} , (solid line) and rate of linear expansion (α) change, $d\alpha/dT$, (dotted line), versus elevated temperature

ature increases to 350°C and 450°C, the temperature does not have the ability to generate more microcracks. Since the temperature exceeds 550°C, more newer microcracks are generated quickly, causing rapid reduction of UCS at 550°C.

The comparison between Figures 2a and 3b shows that the evolution of the rate of the D_{sc} change for specimens cooled in air or water conditions are different, especially for the temperature thresholds of the acceleration of the increment of D_{sc} which are 400°C and 550°C, respectively. To better understand the details of the evolution of the rate of D_{sc} change, two types of the rate of D_{sc} change including dD_{scT} and $d\log D_{scN}$ were defined in Eqs. (2) and (3), respectively.

$$dD_{scT} = (D_{scT2} - D_{scT1}) / (T2 - T1) \quad (2)$$

$$d\log D_{scN} = (\log D_{scN2} - \log D_{scN1}) / (N2 - N1) \quad (3)$$

where D_{scT} is defined as the D_{sc} related to the specimen subjected to a $T(^{\circ}\text{C})$ temperature; D_{scN} is defined as the D_{sc} related to the specimen treated after N thermal cycles.

The comparison between the specimens (1 thermal cycle) cooled in AG condition (marked with gray solid line shown in Figure 4a) and cooled in water (marked with black solid line shown in Figure 4a) shows that the cooling type affects the evolution of the dD_{scT} . As shown in Figure 4a, dD_{scT} of AG condition is in an ascending order before 400°C, then decreases as temperature increases. This result is in consist with previous studies shown in Figure 5 [19–22]. Figure 5 shows that the maximum value of dD_{scT} in different studies are among 400–550°C. In the ascending order stage of dD_{scT} , corresponding rate of linear expansion change ($d\alpha/dT$) also increases which also can be observed in Figure 5. Figure 6 indicates that the acceleration of the increment of $d\alpha/dT$ results in an increment of linear expansion (α). The increasing of α represents the amount of the formed microcracks increasing.

While for the water cooling condition (black solid line in Figure 4a), there is a high dD_{scT} at the initial temperature (300°C) induced by more formed microcracks because of quick cooling process in water. During 350–500°C, temperature effect on dD_{scT} is small until the temperature reaches to 550°C. What's more, Figure 4a also shows that the specimens treated by more numbers of thermal cycles (i.e., 5, 10, 15 and 20) also have a high dD_{scT} at the initial temperature (300°C) but a thoroughly antipodal evolution of dD_{scT} as that of AG condition. dD_{scT} decreases when the values of temperature between 300°C and 450°C, and changes to increase as temperatures higher than 450°C. This indicates that thermal cycle influences the evolution

Figure 6: Linear expansion (α) (solid line) and rate of linear expansion (α) change, $d\alpha/dT$, (dotted line), versus elevated temperature

process of the $dD_{\sigma T}$. More microcracks are produced at 250°C when more of thermal cycles are carried out. The following temperatures ranging from 300°C to 450°C damage the specimens slightly further, causing smaller $dD_{\sigma T}$ with more times of thermal cycle treatment at 300°C and $dD_{\sigma T}$ decreases between 300°C and 450°C. When the temperature exceeds 500°C, thermal cycle treatment damages the specimens more quickly and $dD_{\sigma T}$ starts to increase.

Figure 4b indicates that $d\log D_{\sigma N}$ is in descending order as thermal cycle increases, especially under the thermal cycle number among 1-10. What's more, low temperatures relates to a high and rapid reduction of the $d\log D_{\sigma N}$.

5 Conclusion

According to the experimental results obtained from a series of thermal cycle experiments on 93 with five types of designed temperatures and five types of cycle number of thermal treatments, the following conclusions can be drawn:

1. Uniaxial compressive strength (UCS) of granite specimens decreases as temperature and thermal cycle increase.
2. In general, UCS of granite specimens cooled in water condition after thermal damage treatment are lower than those cooled in air condition.
3. Previous studies have shown that a rapid reduction of UCS of specimens with one thermal cycle treatment and under air cooling condition can be observed at 400°C. While for the specimens treated with more times of thermal cycles and under water cooling condition, a new temperature threshold of

significant reduction of UCS is observed in this study which is 550°C.

4. The same phenomenon can also be observed from the thermal damage index, $D_{\sigma c}$, which increases as temperature and thermal cycle increase.
5. What's more, a thoroughly antipodal evolution of the rate of $D_{\sigma c}$ changes for the specimens treated by several times of thermal cycles and under water cooling condition during heating process is also observed in this study as compared to that for the specimens with one time of thermal treatment and under and under air cooling condition.

Acknowledgement: This research was supported by the National Natural Science Foundation of China (Grant No. 41672279, 41807233) and the Natural Science Foundation of Jiangsu Province (Grant No. BK20180662).

References

- [1] Y. Shen, Y. Wang, Y. Y. Yang, Q. Sun, T. Luo, and H. Zhang, *Construction and Building Materials*, 213 (2019) 156-166.
- [2] I. V. D. Molen, *Tectonophysics*, 73 (1981) 323-342.
- [3] X. L. Xu and M. Karakus, *International Journal of Rock Mechanics and Mining Sciences*, 103 (2018) 195-204.
- [4] F. E. Heuze, *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts*, 20(1) (1983) 3-10.
- [5] Q. Sun, W. Zhang, Y. Zhu, and Z. Huang, *Rock Mechanics and Rock Engineering*, 52(8) (2019) 2691-2699, DOI:10.1007/s00603-019-1733-0.
- [6] P. K. Gautam, A. K. Verma, P. Sharma, and T. N. Singh, *Rock Mechanics and Rock Engineering*, 51 (2018) 2949-2956, DOI:10.1007/s00603-018-1493-2.
- [7] V. Pires, L. G. Rosa, and A. Dionísio, *Construction and Building Materials*, 64 (2014) 440-450.
- [8] P. Vazquez, M. Acuña, D. Benavente, S. Gibeaux, I. Navarro, and M. Gomez-Heras, *Construction and Building Materials*, 104 (2016) 263-275.
- [9] H. Guo, W. Guo, Y. Zhai, and Y. Su, *Construction and Building Materials*, 155 (2017) 427-440.
- [10] D. P. Jansen, S. R. Carlson, R. P. Young, and D. A. Hutchins, *Journal of Geophysical Research: Solid Earth*, 98(B12) (1993) 22231-22243.
- [11] S. Chaki, M. Takarli, and W. P. Agbodjan, *Construction and Building Materials*, 22(7) (2008) 1456-1461.
- [12] S. Shao, P. G. Ranjith, P. L. P. Wasantha, and B. K. Chen, *Geothermics*, 54 (2015) 96-108.
- [13] S. Chen, C. Yang, and G. Wang, *Applied Thermal Engineering*, 110 (2017) 1533-1542.
- [14] S. Q. Yang, P. Ranjith, H. W. Jing, W. L. Tian, and Y. Ju, *Geothermics*, 65 (2017) 180-197.
- [15] J. Hu, Q. Sun, and X. Pan, *Arabian Journal of Geosciences*, 11(2) (2018) 43.

- [16] L. F. Fan, J. W. Gao, Z. J. Wu, S. Q. Yang, and G. W. Ma, *Applied Thermal Engineering*, 140 (2018) 505-519.
- [17] R. Tiskatine, A. Eddemani, L. Gourdo, B. Abnay, A. Ihlal, A. Aharoune, et al., *Applied Energy*, 171 (2016) 243-255.
- [18] Z. T. Bieniawski and M. J. Bernede, *International Journal of Rock Mechanics and Mining sciences&Geomechanics Abstracts*, 16(2) (1979) 137-140.
- [19] G. M. N. Rao and C. R. Murthy, *Canadian Journal of Earth Sciences*, 38(2) (2001) 427-440.
- [20] Q. Sun, W. Q. Zhang, L. Xue, Z. Z. Zhang, and T. M. Su, *Environmental Earth Sciences*, 74 (2015) 2341-2349.
- [21] S. J. Du, H. Liu, H. T. Zhi, and H. H. Chen, *Chinese Journal Rock Mechanics and Engineering*, 23(14) (2004) 2359-2364.
- [22] Y. L. Chen, J. Ni, W. Shao, and R. Azzam, *International Journal of Rock Mechanics and Mining Sciences*, 56(15) (2012) 62-66.
- [23] P. Hartlieb, M. Toifl, F. Kuchar, R. Meisels, and T. Antretter, *Minerals Engineering*, 91 (2016) 34-41. 25
- [24] F. H. Etienne and R. Poupert, *International Journal of Rock Mechanics and Mining Sciences*, 26(2) (1989) 125-134.
- [25] M. H. B. Nasser, A. Schubnel, and R. P. Young, *International Journal of Rock Mechanics and Mining Sciences*, 44 (2007) 601-616.
- [26] M.H.B. Nasser, B.S.A. Tatone, G. Grasselli, and R.P. Young, *Pure and Applied Geophysics*, 166 (2009) 801-822.
- [27] C. Insera, S. Biwa, and Y.Q. Chen, *International Journal of Rock Mechanics and Mining Sciences*, 62(5) (2013) 96-104.