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Experimental study on mechanical properties of granite under different cooling methods after thermal treatment

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Abstract: Static uniaxial compression tests were conducted on 16 granite specimens after thermal treatment using a heating device and an electro-hydraulic servo pressure-testing machine. The effects of air cooling and water cooling on the physical and mechanical properties of the high-temperature granite specimens were studied. Test results showed that the longitudinal wave velocities of the high-temperature specimens gradually decreased after they were cooled by water and air. The peak stress and elastic modulus of the samples decreased gradually with an increase in temperature, whereas their peak strain increased gradually. The effects of peak stress and peak strain were considerably more evident when cooling by water than by air. This result demonstrated that the thermal cracking of the granite specimens, and consequently, their internal micro-fractures, further developed when the specimens were cooled by water.

Keywords: granite; high temperature effect; cooling method; mechanical properties

0 Introduction

The processes of exploring and utilizing enhanced geothermal systems involve the drilling of inner thermal rock (granite). The surrounding rocks of the wellbore are influenced by the low temperature well-drilling liquid, paste, and water, which lead to the rapid decrease in the temperature around the well. The physical characteristics of the surrounding rocks of the borehole can be changed by the coupling effects of the temperature, seepage, and stress fields, which can easily lead to complex issues, such as the thermal rupture of the surrounding rocks, necking, hole sloughing, the sticking of tools, and the crashing of the casing pipe (Xi, 2009; Li *et al*., 2011, Yang & Hu, 2001). In recent years, scholars worldwide have conducted considerable studies on the physical and mechanical characteristics of granite under or after the effect of high temperature (Yin *et al*., 2016, Xu *et al*., 2014; Qin, 2017; Du *et al*., 2003). Rocks are typically cooled by air, and Chinese scholars, such as Xiong *et al*. (2018), have developed systematic summaries and analyses on this aspect (Xiong & Yu, 2018). Xi *et al*. (2010) experimentally studied the behavior of thermal granite cooled by water, but they did not analyze the differences between air cooling and water cooling. To date, no report is yet available on the effects of both cooling methods on granite's physi-

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cal and mechanical characteristics after exposure to high temperature. Accordingly, this paper mainly discusses this issue through experimental studies, which provide the reference parameter values for the borehole stability analysis, and numerical simulations of the thermal cracking of high-temperature borehole rocks that come in contact with low-temperature liquid when high-temperature dry hot rocks are drilled.

1 General situation of the experiment

1.1 Preparation of the specimens

The experimental rocks were outcrop samples obtained from Jingyuetan, Changchun. The fresh samples appeared gray and white and exhibited weak weathering. X-ray diffraction analysis indicated that the main mineral components of the specimens were feldspar (62%), quartz (23%), black mica (8%), flicker (5%) and other components (2%). The average density was 2.82 g/cm^3. A total of 16 specimens were obtained according to the Standard for Test Methods of Engineering Rock Mass (GB/T 50266-2013), using coring machines, grading machines; and microtomes to perform drilling. The size of the specimens was Φ50 × 100 mm.

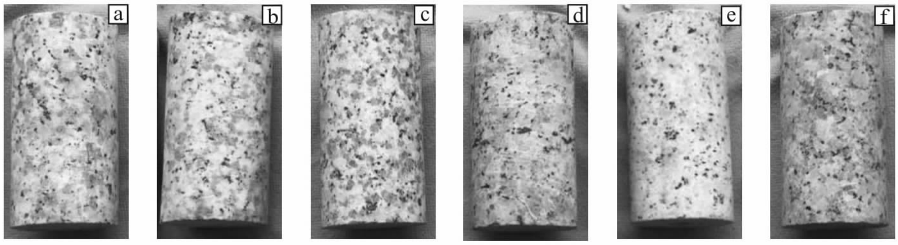
1.2 Devices and experimental methods

An SXL-1200C box-type resistance high-temperature furnace was used for heating, and the highest temperature could reach 1 200℃. This device is illustrated in Fig. 1. Eight temperatures, namely, 25℃, 100℃, 200℃, 300℃, 400℃, 500℃, 600℃, and 700℃, were used in the experiment. Every group comprised two samples. The heating rate was 5℃/min. The target temperature was maintained for 2 hours to ensure that the rock samples were heated uniformly. In the experiment, the specimens were removed from the furnace immediately after heating, cooled by air (18℃) and water (18℃) for 30 min, and then dried for 96 h. The researchers utilized a microcomputer to control the electro-hydraulic servo pressure tester and conduct the uniaxial compression test. Different masses of samples were measured before and after heating using an electronic balance (accuracy: 0.1 g). The RSM-SY-type nonmetallic wave velocity tester of Wuhan Science and Technology in Rock was used to test longitudinal wave velocity. The specimens were placed horizontally during the test. The researchers applied petroleum jelly on both ends to press the emission transducer and the receiving transducer of the wave velocity meter on both ends of a sample, achieving firm contact with the sample.

Fig. 1 SXL-1200C high temperature test chamber

The appearance of the samples that were cooled by air after heating at different temperatures is shown in Fig. 2. Under ambient state, the colors black, white, and red were shown regularly, but gray was the dominant feature given that the main components of granite are quartz, black mica, and feldspar. The variation in color barely changed before 400℃. As temperature increased, color gradually changed from gray to pale red. Such change was even more evident when temperature was over 600℃. After maintaining 700℃ for 2 hours, the samples started to crack, and fragments broke off, thereby indicating that the samples´ interior were severely destroyed. Accordingly, the compression test could not continue.

When temperature was high, it took more time for the samples to soak up the water during water cooling, and a small amount of bubbles emerged. No change in the samples' appearance was observed between cooling by air and cooling by water after the samples dried out.



(a) t = 100℃; (b) t = 200℃; (c) t = 300℃; (d) t = 400℃; (e) t = 500℃; (f) t = 600℃; (g) t = 700℃.

Fig. 2 Appearance morphology of samples after different high temperature effects

2 Results and analysis of the experiment

2.1 Mass loss and longitudinal wave velocity

After heating, different amounts of water in the samples' interior will evaporate when the temperature is over the critical value. Moreover, various minerals will produce serious physical and chemical reactions, such as decomposing and dehydroxylation, which will ultimately lead to a change in mass (Zhang, 2017). The mass loss rates of the samples used in this study were relatively small; therefore, the researchers could use the mass loss rate to demonstrate mass change. Different loss rates under various cooling methods are shown in Fig. 3. When temperature was within the range of 25℃ to 600℃, the mass loss rate consistently increased with increasing temperature. However, the maximum value was less than 0.2% because the interior of granite barely had flaws and water. After the water-cooled samples were dried for 96 hours, a small amount of water remained and compensated for the mass loss of the samples caused by heating. Therefore, the mass loss rate resulting from water cooling was less than that resulting from air cooling. In general, the mass loss rate of heating is extremely small when cooling under different methods.

Samples can experience thermal cracking when they come in contact with water after heating, and the internal organizational structure will exhibit corresponding changes (Xi & Zhao, 2010). The thermal cracking of the rocks surrounding well bore and the stability of the borehole should be studied by utilizing longitudinal wave velocity to analyze rock damage features and thermal cracking, which has a significant meaning. As temperature increased, longitudinal wave velocity decreased gradually after the high-temperature samples were cooled by air and water. The maximum velocity occurred under ambient condition, as shown in Fig. 4.

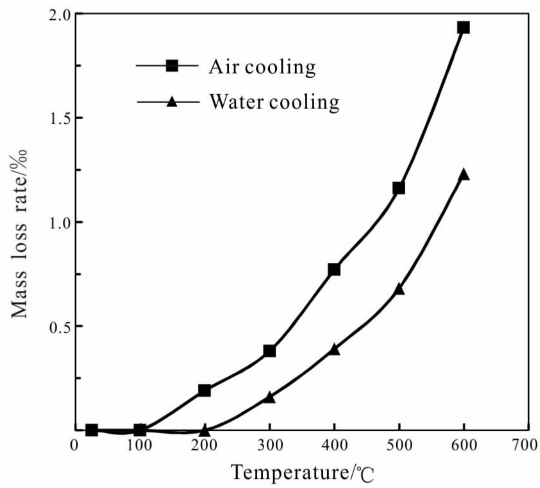


Fig. 3 Mass loss rate-temperature after air cooling and water cooling

The decrease in wave velocity demonstrated that the internal structure had changed under heating. With the development of micro-cracks, micro-damages occurred in the samples. The development of thermal cracks intensified and the number of inner micro-cracks increased because of the sudden decrease in temperature caused by water cooling. The micro-damages decreased wave velocity, thereby indicating that macroscopic mechanical properties would change dramatically.

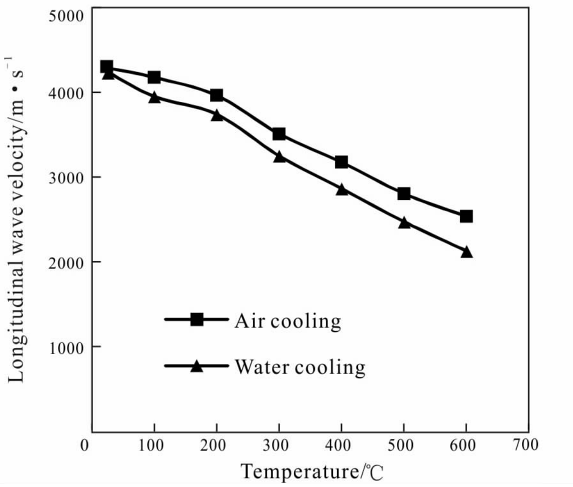


Fig. 4 Longitudinal wave velocity-temperature after air cooling and water cooling

Fig. 5 Uniaxial compression failure mode of sample 1

2.2 Uniaxial compressive experiments

The destruction modes of the samples cooled using two different methods and the rock samples that were not heated and cooled were basically uniform, and shearing was dominant. The destruction mode of Sample 1 is illustrated in Fig. 5. The dominant mechanical properties of the uniaxial compression experiment were provided in Table 1.

The change law of the samples' elastic modulus is shown in Fig. 6. Elastic modulus decreased with increasing temperature under the two different cooling conditions. The average elastic modulus of the untreated samples was 35.95 GPa. When temperature increased to 400 ℃, the elastic modulus of the samples

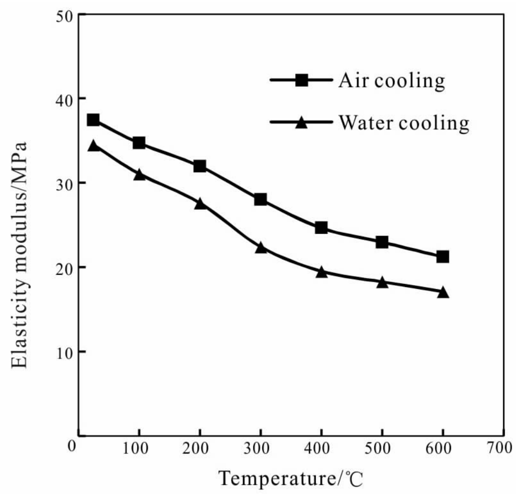


Fig. 6 Elastic modulus-temperature curves after air cooling and water cooling

Table 1 Test results of main mechanical properties of samples

Temperature	No.	Air cooling			No.	Water cooling		
		PPS/MPa	PSN/%	EM/GPa		PPS/MPa	PSN/%	EM/GPa
25	1	172.29	0.3	37.43	2	163.4	0.3	34.47
100	3	168.62	0.32	34.69	4	157.68	0.35	31.05
200	5	164.3	0.35	31.94	6	149.8	0.46	27.59
300	7	159.98	0.4	28.00	8	139.71	0.55	22.40
400	9	148.16	0.5	24.63	10	122.47	0.76	19.51
500	11	132.94	0.65	22.95	12	108.13	0.95	18.25
600	13	107.06	1.05	21.20	14	75.13	1.2	17.11
700	15	–	–	–	16	–	–	–

Note: PPS-peak stress; PSN-peak strain; EM-elastic modulus.

cooled by air was 24.63 GPa (with 31.49% decrease), whereas the elastic modulus of the samples cooled by water was 19.51 GPa (with 45.73% decrease). The difference in elastic modulus between the two cooling methods was 14.24%, which demonstrated that water is an important factor for decreasing the samples' elastic modes.

Peak stress and peak strain are two essential control targets in rock engineering design. The shape of peak stress and the strain-temperature diagram for the two different cooling methods are shown in Fig. 7. Peak stress consistently decreased with increasing temperature, whereas peak strain gradually increased. The samples destroyed by air cooling were compared with those untreated with high temperature. When temperature ranges from 100℃ to 600℃, peak stress decreased by 2.13%, 4.64%, 7.14%, 14.01%, 22.84%, and 37.86%. The samples destroyed by water cooling were also compared with those untreated with high temperature. When temperature ranges from 100℃ to 600℃, peak stress decreased by 3.50%, 8.32%, 14.50%, 25.05%, 33.82%, and 54.02%. The variation in peak stress was relatively small when temperature was below 300℃, and peak strain increased gradually. The variation in peak stress and peak strain increased conspicuously after 300℃. Water cooling exerted more effects on the peak stress and peak strain of the samples than air cooling, thereby indicating that water cooling resulted in more thermal cracking on the samples that led to internal microcracks compared with the damage caused by high temperature .

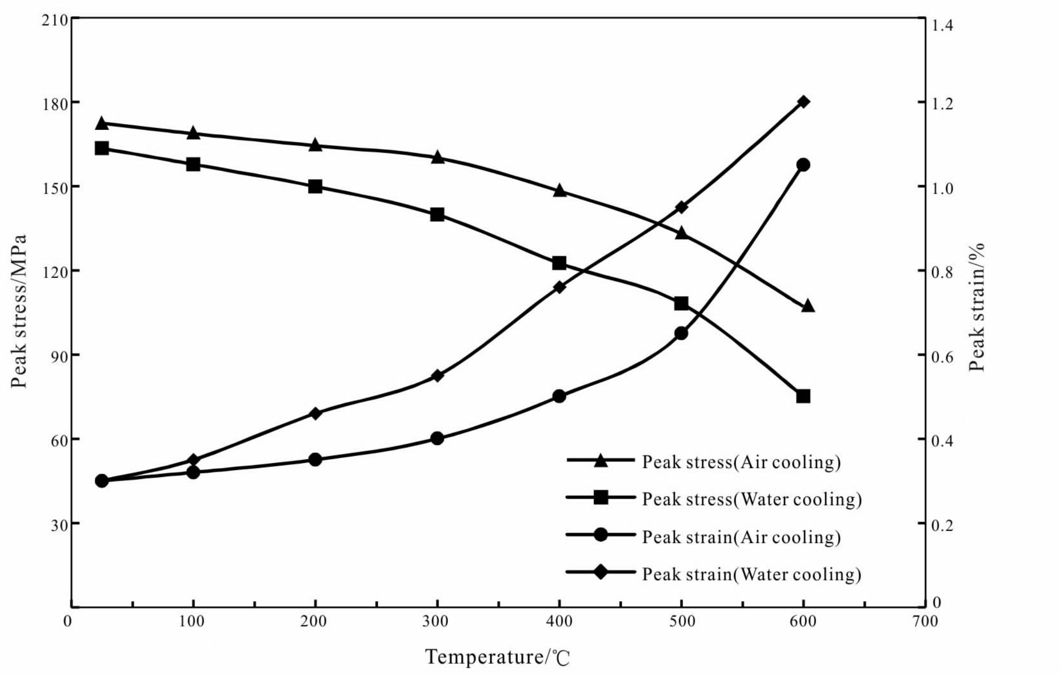


Fig. 7 Peak stress, peak strain vs- temperature after air cooling and water cooling

3 Conclusions

This study investigated the physical and mechanical properties of granite through a uniaxial compression experiment performed on high-temperature specimens that were cooled under the two different cooling conditions. The temperature ranges from 25℃ to 700℃. The thermal cracking mechanics of the granite samples cooled by water was also discussed. The main conclusions are as follows.

(1) The color of the samples gradually changed from gray to pale red with the increase in temperature. The shearing damage of the samples was dominant under both cooling methods.

(2) After the high-temperature samples came in contact with cold water and air, longitudinal wave velocity gradually decreased. Water cooling led to a more evident decreasing range of wave velocity compared with that of air cooling. When temperature reached 600℃, a difference of 9.63% existed between the longitudinal wave velocities under the two cooling methods.

(3) Peak stress and modulus of elasticity decreased gradually with increasing temperature, whereas peak strain increased gradually. Water cooling exerted more evident effects on the samples' peak stress and peak strain than air cooling. Under the same temperature condition, the maximum difference in the peak stresses of the two cooling methods was 16.16%, which indicated that a sudden change in temperature led to further thermal cracking and the micro-cracks of the high-temperature samples were caused and developed by water cooling.

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