Research Article

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Assessment of impact mechanical behaviors of rock-like materials heated at 1,000°C

<https://doi.org/10.1515/htmp-2020-0040>

received November 18, 2019; accepted January 17, 2020

Abstract: Rock acts as a natural brittle material and demonstrates reactions to various dynamic disturbances and high temperature. Mechanical property fluctuations under high temperature and dynamic load for rock materials including marble, sandstone and granite are studied in an underground project of Qinling Mountain in China, exposed to 1,000°C treatments and different strain rate impact loadings. Two main research issues are explored: (1) variations of strength and failure modes of the same high-temperature rock type under different strain rate impact loadings. (2) Comparison of strength and failure modes of three high-temperature rock types under same strain rate impact loadings. Experimental results indicate that both 1,000°C temperature and the strain rate exert significant influence on dynamic compressive strength, and dynamic compressive increase factor and failure modes of three rock types. However, the influences of high temperature and strain rate on different rock types have obvious differences.

Keywords: impact mechanical behaviors, rock-like materials, strain rate, 1,000°C treatment, SHPB

1 Introduction

Rock has been widely utilized as a natural building material in engineering practices such as buildings, roads and tunnels throughout the history of architecture and civil works, with most cultural heritage historic buildings

constructed from stone [1–3]. Strength is an integral mechanical property to be determinate in building materials in which cement, concrete, rocks or bricks are used [4,5]. Brittle fracture is a failure phenomenon occurring in rock materials and has been intensively investigated in rock physics and geotechnical engineering [6–13]. The application of rock in various high-temperature environments, such as the disposal of high-level nuclear waste and fire protection engineering, where temperature near the fire source reaches 1,000°C, has prompted experimental investigations with findings that strength and failure modes of rock exposed to high-temperature treatments are distinct from those exposed only to room temperature conditions [14–18].

Rock-related engineering projects, e.g. blast explosions, earthquakes and underground excavation, often subject high strain rate loadings inducing severe degradations in rock materials and creating strain rate effects and responses that differ from materials under static loading conditions [19–24]. Accurate characterizations of rock strengths and failure modes under high strain rate loadings are crucial to rock engineering applications.

Understanding mechanical responses of rock exposed to high temperature to impact or explosive loading is important for effective protection of underground rock engineering. But the strength and failure modes of rock exposed to high temperature and high strain rate loadings are far from those of the single high-temperature condition or single impact load condition. Fundamental questions related to strength and failure modes of rock remain unanswered due to lack of experimental information. Mechanical parameters obtained by conventional static high temperature or dynamic impact room temperature mechanical testing cannot be applied in design and construction of underground rock engineering. Conducting mechanical tests on rock exposed to high temperature and high strain rate loadings can accurately reflect the actual stress state, providing estimates for reliable simulation of underground structural response to blast loading.

In this study, three rock types were subjected to different high strain rate impact loadings after treatment at 1,000°C to experimentally determine the effects of

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high-temperature and high strain rate impact loadings on dynamic compressive strength (DCS), DCS increase factor and failure modes. The objectives of this research are as follows:

1. To assess variation characteristics of strength and failure modes of the same high-temperature rock type under different strain rate impact loadings.
2. To draw comparisons of strength and failure modes among three different high-temperature rock types under the same strain rate impact loading.

2 Materials and experimental program

2.1 Apparatus

The Φ 100 mm split Hopkinson pressure bar (SHPB) testing device is the core of the testing system (see Figure 1), which is an experimental technique commonly used in the study of the constitutive laws of materials at high strain rates. It consists of three components.

1. The main equipment: The striker bar, incident bar and transmission bar were 500, 4,500 and 2,500 mm long, respectively, and both of the bars were 100 mm in diameter.
2. The energy system, made up of air compressor, high pressure air bag and piping.
3. The testing system, made up of strain gauges and ultra-dynamic apparatus as well as the dynamic test and analysis equipment.

A projectile impacts the free end of the incident bar, thus developing a compressive longitudinal incident wave. Once this wave reaches the bar-specimen interface, part of it is reflected, whereas the other part travels through the specimen and develops the transmitted wave in the incident bar. With the strain gauges that are glued on the incident bar and transmission bars, these three basic waves are recorded. These strains are then used to compute the strain rate, strain and stress in the specimen as follows [25,26]:

$$\begin{aligned}\sigma_s(t) &= \frac{EA}{2A_s} [\varepsilon_i(t) + \varepsilon_r(t) + \varepsilon_t(t)] \\ \dot{\varepsilon}_s(t) &= \frac{c}{l_s} [\varepsilon_i(t) - \varepsilon_r(t) - \varepsilon_t(t)] \\ \varepsilon_s(t) &= \int_0^t \dot{\varepsilon}_s(\tau) d\tau,\end{aligned}\quad (1)$$

where E is Young's modulus of bars; c is wave velocity in bars; A and A_s are cross-sectional areas of bars and specimen, respectively; l_s is original length of specimen; ε_i , ε_r and ε_t are incident, reflected and transmitted strain, respectively; and τ_1 and τ_2 are time delays of reflected and transmitted pulses, respectively.

A high-temperature heating experimental setup is outlined in Figure 2. It consists of three components:

1. RX3-20-12 box-type resistance furnace: the device has six built-in thermocouples used for heating, with silicon carbon rod elements used in heating, high-performance fiber used in insulation.
2. The temperature control box: automatic in temperature control and heating, with the design maximum operating temperature up to 1,200°C.

Figure 1: Apparatus of 100 mm diameter SHPB.

3. A rail: to provide convenience for taking or placing specimens at high temperatures.

2.2 Samples and heating process

The Qinling Mountains stretch across central China, 1,500 km from east to west and 100–150 km from north to south. In this study, the rock samples were cored from fresh intact rock blocks belonging to an excavation of 50–150 m underground from the Qinling Mountains. The surface of the rock sample is complete without obvious defects such as holes and cracks. The rock samples are air dried in the natural state at room temperature. Three cylindrical specimens of 100 mm diameter rock samples of marble, sandstone and granite were used in this study. By using a high-speed rotary saw, the drilled specimens were cut into lengths of 50 mm with the ratio of length to diameter maintained at 0.5. An end face grinder was then used to grind the specimens, and inspections were conducted to confirm evenness and perpendicularity with respect to the vertical axis [27]. No bedding plane was observed in the specimens. The average density of marble, sandstone and granite samples are 2,600, 2,750 and 2,650 kg/m³, respectively, and complete mineral composition of the three rock types are listed in Table 1. The specimens were subjected to longitudinal wave velocity testing utilizing a RSM-SY5N nonmetal ultrasonic testing analyzer after dimensions were measured. The specimens were then heated in the heating setup at the rate of 10°C/min until 1,000°C and

were kept at constant temperature for 3 h. The 1,000°C high-temperature specimens were then placed in the heating setup to cool to room temperature. Each temperature group is equipped with no less than three specimens. Three rock types exposed to room temperature and 1,000°C treatment are shown in Figures 3 and 4.

3 Static compressive test

The test samples used in static compressive test are prepared using the same processing method specified in Section 2.2. Cylindrical specimens of the length-to-diameter ratio equal to 2 (50 mm diameter) were cored for uniaxial static compression tests [27]. The typical static compressive stress–strain curves of three rock types are shown in Figure 5. The static compressive strengths are shown in Figure 6. The longitudinal wave velocities are shown in Figure 7. Static compressive strengths of marble, sandstone and granite samples at room temperature are 60.2, 59.7, 90.4 MPa, respectively. Static compressive strengths of three rock types after 1,000°C treatment are 10.9, 10.9 and 30.5 MPa, and when compared with room temperature, it decrease by about 81.89%, 81.74% and 66.26%, respectively. Longitudinal wave velocities of marble, sandstone and granite samples at room temperature are 5,173, 2,060 and 4,262 m/s, respectively. Longitudinal wave velocities of three rock types after 1,000°C treatment are 1,456, 360 and 557 m/s, and when compared with room

Figure 2: High-temperature heating experimental setup.

Table 1: Summary table of mineralogical composition of rock specimens. All values in wt%

Mineral composition/%	Quartz	Calcite	Plagioclase	K-feldspar	Montmorillonite	Chlorite	Illite
Marble	1	3	—	—	—	—	—
Sandstone	52	27	8	6	1	2	3
Granite	17	—	37	8	—	—	—

Mineral composition/%	Biotite	Amphibole	Diopside	Magnetite	Dolomite	Muscovite	Talc
Marble	—	2	—	—	90	3	1
Sandstone	—	—	—	—	1	—	—
Granite	18	12	4	4	—	—	—

temperature, it decrease by about 71.85%, 82.52% and 86.93%, respectively.

4 Dynamic compressive test results and discussions

In recent years, most studies have focused on simulating high-strain rate loading in laboratory tests [28–31]. Dynamic behavior of rock after high-temperature treatment at high strain rates differs considerably from that observed at room temperature, and practical

applications often require mechanical operation of high-temperature rock under dynamic conditions. Impact loading rate of projectiles is controlled at 11.0, 12.0, 13.0, 14.0 and 15.0 m/s by adjusting the air pressure and the specific location of projectiles in the launch barrel, corresponding to five different strain rates of rock material.

The T2 red copper sheet with a thickness of 1 mm is used as the waveform shaper, and the diameter is 30–45 mm corresponding to the impact compression test. Before the test, the copper piece is pasted at the center of the contact end of the incident bar and the bullet. During the impact loading test, the copper material with the lower yield strength absorbs the

Figure 3: Three rock samples exposed to room temperature. **Figure 4:** Three rock samples exposed to 1,000°C treatment.

Figure 5: Typical static compressive stress–strain curves of three rock types.

energy of a part of the incident pulse and then filters the high-frequency oscillation of the incident wave. A smoother sine wave or a half sine wave can be obtained. Waveform shaping technology can effectively extend the rising time of the incident stress wave and ensure the stress uniformity of the sample. Figures 8 and 9 illustrate the typical waveforms of rock impact compression tests exposed to room temperature and 1,000°C treatment. The SHPB test results on rock exposed to room temperature and 1,000°C treatment are summarized in Tables 2–4. Figures 10 and 11 illustrate the typical dynamic compressive stress–strain curves of rock (only list stress–strain curves of marble).

Figure 7: Longitudinal wave velocity of three rock types exposed to room temperature and 1,000°C treatment.

Figure 8: Typical waveforms of rock exposed to room temperature.

Figure 6: Static compressive strength of three rock types exposed to room temperature and 1,000°C treatment.

Figure 9: Typical waveforms of rock exposed to 1,000°C treatment.

Table 2: Summary of mechanical parameters of marble exposed to room temperature and 1,000°C treatment

Marble	Temperature	Strain rate (S^{-1})	DCS (MPa)	DCS increase factor	Average static compressive strength (MPa)	Average longitudinal wave velocity (m/s)
	Room temperature	65.1	169.4	2.84	60.2	5,173
		95.0	201.2	3.37		
		101.4	241.8	4.05		
		115.2	259.8	4.35		
		123.8	284.9	4.77		
	$T = 1,000^{\circ}C$	114.9	44.8	4.10	10.9	1,456
		175.6	46.2	4.22		
		180.5	47.9	4.38		
		186.1	49.5	4.52		
		191.4	50.6	4.63		

4.1 DCS

Variation characteristics of DCS of three rock types exposed to room temperature and 1,000°C treatment under different strain rates are presented in Figure 12. DCS exposed to room temperature and 1,000°C treatment

exhibit concentration in two different regions with nearly no overlap, indicating that under the same impact velocity, two different temperature conditions exert an exceptional influence on DCS and strain rate of the three rock types. The DCS sharply reduces, and the strain rates significantly increase following 1,000°C treatment,

Table 3: Summary of mechanical parameters of sandstone exposed to room temperature and 1,000°C treatment

Sandstone	Temperature	Strain rate (S^{-1})	DCS (MPa)	DCS increase factor	Average static compressive strength (MPa)	Average longitudinal wave velocity (m/s)
	Room temperature	93.1	173.5	2.91	59.7	2,060
		123.5	179.4	3.01		
		135.2	203.7	3.41		
		154.9	218.9	3.67		
		166.0	226.8	3.80		
	$T = 1,000^{\circ}C$	145.3	57.3	5.24	10.9	360
		190.0	51.0	4.66		
		224.1	56.5	5.16		
		237.8	56.6	5.17		
		248.4	56.8	5.19		

Table 4: Summary of mechanical parameters of granite exposed to room temperature and 1,000°C treatment

Granite	Temperature	Strain rate (S^{-1})	DCS (MPa)	DCS increase factor	Average static compressive strength (MPa)	Average longitudinal wave velocity (m/s)
	Room temperature	65.5	201.8	2.23	90.4	4,262
		75.6	220.0	2.43		
		98.6	245.8	2.72		
		108.0	289.4	3.20		
		116.9	347.2	3.84		
	$T = 1,000^{\circ}C$	187.5	149.4	4.90	30.5	557
		194.2	143.2	4.70		
		198.8	154.4	5.06		
		202.6	158.6	5.20		
		220.1	163.4	5.36

Figure 10: Dynamic compressive stress–strain curves of marble exposed to room temperature.

indicating that 1,000°C treatment produces severe degradations in DCS and strain rate. Specific test and analysis results are as follows: strain rate-enhanced performance on DCS of three rock types at room temperature is obvious with influences of strain rate on marble and granite much greater than on sandstone. Under the same impact velocity, the DCS of granite is greatest, followed by marble, with DCS of sandstone the least. Alterations in the strain rate-enhanced performance on DCS occur following 1,000°C treatment as DCS of marble and granite experience increases, with the increase significantly less than at room temperature, while DCS of sandstone experiences little change. In addition, unlike room temperature conditions, under the same impact velocity, DCS of granite is greatest, while

Figure 12: Dynamic compression strength of three rock types exposed to room temperature and 1,000°C treatment.

DCS of marble and sandstone is minimal. But, in general, the DCS of sandstone is slightly greater than marble, showing that the weakening effect due to 1,000°C on marble DCS is most serious.

Dynamic compressive increase factor (DCIF) is the ratio of the dynamic and static compressive strength of rock material, reflecting the increased amplitude in DCS of rock under impact loading. Variation characteristics of DCIF of three rock types exposed to room temperature and 1,000°C treatment under different strain rates impact loadings are presented in Figure 13. Compared with the static compressive strength, DCIF of the three rock types increases partially independently of temperature conditions as DCIF is generally greater than 1. Strain rate-enhanced performance on DCIF is apparent at room

Figure 11: Dynamic compressive stress–strain curves of marble exposed to 1,000°C treatment.

Figure 13: Dynamic compression strength increase the factor of three rock types exposed to room temperature and 1,000°C treatment.

temperature with the influence of strain rate on marble and granite much greater than sandstone. DCIF of marble is greatest under the same impact velocity followed by sandstone with DCIF of granite the least, indicating that the increased amplitude in DCS of marble is the greatest. Modifications occur in strain rate-enhanced performance on DCIF following 1,000°C treatment. DCIF of marble and granite exhibit slight increases with the increase of strain rate although significantly less than at room temperature, whereas DCIF of sandstone remains nearly unchanged.

4.2 Failure modes

Failure mode variation characteristics of the three rock types exposed to room temperature and 1,000°C treatment under different strain rates impact loadings are presented in Figures 14–16. Failure mode reflects the rock stress state as a result of interactions among rock micro-cracks. High temperature of 1,000°C and the strain rate exert significant influence on failure modes of the three rock types as shown in Figures 14–16. Failure modes of each rock type at room temperature, when subjected to impact loading exceeding the ultimate rock

strength, demonstrate tensile splitting failure characterized by tensile fracturing in parallel to the axial direction rather than axial compression failure. Differences exist in failure modes for marble and granite as samples are typically broken into pieces with the increasing strain rate with the amounts of failure pieces gradually increasing and pieces tend to be uniform. Sandstone failure modes manifest typically as samples exhibiting an intact core and corroded edges. Sandstone samples will not be destroyed immediately after the axial tensile failure occurred and may still bear certain axial pressure in the shear plane formation throughout the sample. The failure of sandstone samples is significant with the increasing strain rate, often rapidly disintegrating after reaching the peak strength. Because the sample failure process lasts shorter, end effect limits the vertical development of splitting cracks, thus resulting in the failure modes characterized by edge avalanche and shear buckling in the central area of rock pillar treatment. Internal damage in rock, after 1,000°C treatment, is extensive and induces significant changes in failure modes of each rock type compared with room temperature. The failure mode for marble and sandstone is far more severe than with room temperature as failure pieces rapidly increase, and pieces tend to be in the powder form. Failure modes for granite exhibit tensile

Figure 14: Failure modes of marble exposed to room temperature and 1,000°C treatment. (a) 65.1 s^{-1} , (b) 95.0 s^{-1} , (c) 101.4 s^{-1} , (d) 115.2 s^{-1} and (e) 123.8 s^{-1} . Room temperature: (a) 114.9 s^{-1} , (b) 175.6 s^{-1} , (c) 180.5 s^{-1} , (d) 186.1 s^{-1} and (e) 191.4 s^{-1} .

Figure 15: Failure modes of sandstone exposed to room temperature and 1,000°C treatment. (a) 93.1 s^{-1} , (b) 123.5 s^{-1} , (c) 135.2 s^{-1} , (d) 154.9 s^{-1} and (e) 166.0 s^{-1} . Room temperature: (a) 145.3 s^{-1} , (b) 190.0 s^{-1} , (c) 224.1 s^{-1} , (d) 237.8 s^{-1} and (e) 248.4 s^{-1} .

splitting failure similar to that of sandstone at room temperature with a typical intact middle core and edge corrosion.

As a structural medium containing various defects, rock exhibits original and spontaneous defects in the deformation process leading to stress nonuniformity.

Figure 16: Failure modes of granite exposed to room temperature and 1,000°C treatment. (a) 65.5 s^{-1} , (b) 75.6 s^{-1} , (c) 98.6 s^{-1} , (d) 108 s^{-1} and (e) 116.9 s^{-1} . Room temperature: (a) 168.6 s^{-1} , (b) 174.1 s^{-1} , (c) 184.8 s^{-1} , (d) 214.1 s^{-1} and (e) 255.9 s^{-1} .

Local tensile stress concentration occurs as a result in the sample rendering stress nonuniformity, which is the decisive factor in tension failure. Splitting failure mode is often then presented as tensile strength of the rock that is extremely low in the compression process.

The comparative analysis of the DCS and failure modes of rock types exposed to room temperature and 1,000°C treatment under different strain rate impact loadings reveals that the failure mode and strength correlations are nearly nonexistent for the same rock type subjected to different temperature treatments and strain rates and for different rock types subjected to the same external environment. Variation characteristics of failure modes and strength affected by temperature and strain rate are also revealed to be dissimilar.

4.3 Microstructure characteristics

The microstructure characteristics of rock directly determine its macroscopic mechanical response. Taking marble as an example, the typical scanning electron microscope images of fracture failure of rock samples exposed to room temperature and 1,000°C treatment under impact loading are shown in Figures 17 and 18. At room temperature, the fracture forms of marble under impact loading are very rich and contain a lot of information about the crystal structure and micro-crack changes in the rock. The failure form is mainly transgranular fracture. Temperature has a significant influence on the mineral composition and crystal structure of rocks, so the microstructure characteristics

Figure 17: Fracture morphology of marble exposed to room temperature.

Figure 18: Fracture morphology of marble exposed to 1,000°C treatment.

of rocks under the influence of high temperature are obviously different from those under normal temperature. After 1,000°C treatment, the fracture morphology of marble is dominated by obvious plastic fracture, with a large number of plastic fracture characteristics such as slip separation and dimples. This indicates that the marble has begun to undergo a brittle-plastic transition, which is also reflected in macroscopic mechanical tests.

5 Conclusions

The influence of the strain rate on DCS and DCIF of marble and granite at room temperature is much greater than sandstone. Under the same impact velocity, the DCS of granite is superior, followed by marble, with DCS of sandstone exhibiting the least; the DCIF of marble is superior, with granite exhibiting the least. Following 1,000°C treatment, with the increase of the strain rate, the DCS and DCIF of marble and granite demonstrate some increase, although significantly less than at room temperature, while DCS and DCIF of sandstone change only minimally. The DCS of granite is superior under the same impact velocity, while DCS of marble and sandstone are minimal. The DCS of sandstone is typically slightly more than marble, indicating that the weakening effect of high temperature 1,000°C on marble DCS is most significant.

Failure mode reflects the stress state of rock as a result of interaction among rock micro-cracks. Failure modes of the three rock types at room temperature reveal tensile splitting failure characterized by tensile

fracturing in parallel to the axial direction rather than axial compression failure. Samples are typically broken into pieces for marble and granite, and in case of sandstone, samples typically exhibit an intact middle core and edge corrosion. Failure modes of the three rock types change significantly compared with room temperature following 1,000°C treatment. For marble and sandstone, failure pieces rapidly increase and tend to be powder like for marble and sandstone, and for granite, failure modes exhibit tensile splitting failure similar to that of sandstone at room temperature with an intact middle core and edge corrosion.

Acknowledgments: This work has been supported by The National Natural Science Foundation of China (No. 51378497).

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