Research Article

Effect of Temperature and Strain Rate on the Brittleness of China Sandstone

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To quantitatively study the influence of temperature and strain rate on the brittleness of sandstone, the mechanical parameters of sandstone under different temperatures and strain rates are collected from the previous literature, and two empirical equations for calculating rock brittleness are used to quantitatively calculate and evaluate the brittleness of sandstone. The results show that both BI_1 and BI_2 can characterize the brittleness of sandstone, but the applicable conditions are different. The BI_1 method is more accurate in calculating the variation in the sandstone brittleness with a strain rate, while the BI_2 method is more accurate in calculating its variation with temperature. The brittleness of sandstone increases with the increase in the strain rate, especially when the strain rate exceeds 100 s^{-1} . Under low-temperature conditions, the strength and brittleness of rocks increase due to the strengthening of ice. Under the condition of high temperature, the thermal damage to sandstone is intensified after 400°C , and the quartz phase changes after 600°C , which leads to the increase in microcrack density and the decrease in brittleness of sandstone. The conditions of low temperature and high strain rate are beneficial to the enhancement of sandstone brittleness.

1. Introduction

Brittleness is a very important property of rock. It can be used as an index of safety risk in resource exploitation and engineering construction projects. For example, brittleness is an important property for shale gas compressibility measurement and evaluation and is a basic parameter for reservoir evaluation. Rock bursts are directly related to the brittle fracture of rock masses and the instability failure of surrounding rock structures [1]. Brittleness also is a key index of rock drillability, which plays an important role in improving tunneling speed and reducing tool wear [2]. Therefore, it is important to evaluate the brittleness of rock accurately in the process of resource development and engineering construction.

Definitions of brittleness vary across disciplines and fields, and at present, there is no unified definition. Nevertheless, many scholars have carried out in-depth research

on the brittleness of rock and established different evaluation indexes of brittleness [3, 4]. For example, Jarvie et al. [5] defined the percentage of brittle minerals in rocks as a BI. Altindag [6] defined the BI of rock as the ratio of compressive strength to tensile strength. There are many definitions of BI based on curve shapes [7–9] and energy relationships [10] in stress-strain curves. Hucka and Das [11] defined a BI as the ratio of elastic strain to total strain in a stress-strain curve. Tarasov and Potvin [12] defined a BI for rocks as the ratio of rupture energy to excess (released) energy.

Temperature is one of the important factors affecting rock mechanical properties. Geotechnical engineering and artificial freezing engineering in cold areas make the surrounding rock of the engineering structure be subject to periodic low-temperature effects or long-term low-temperature freezing, and its strength characteristics are very different from normal temperature conditions. Under high-temperature conditions, sandstone produces thermally

TABLE 1: Characteristics of the reviewed dynamic loading of sandstone.

Rock type	Ref.	Site	Main mineral	Number of samples	Sample size (mm)	Test equipment	Test process
Sandstone	Gong et al. [49]	Shandong, China	42% Qtz; 35% Pl; 9% Cal; 8% Zeo; 5% Kfs; 1% Op	22	$\Phi 50 \times 100$ mm	Conventional SHPB system	45 s^{-1} , 59 s^{-1} , 66 s^{-1} , 84 s^{-1} , 91 s^{-1} , 96 s^{-1} , 116 s^{-1} , 135 s^{-1}
Fine sandstone	Hou [50]	Shanxi, China	/	36	$\Phi 50 \times 25$ mm	$\Phi 74$ mm SHPB test device	10 s^{-1} , 25 s^{-1} , 95 s^{-1} , 100 s^{-1} ; 100°C , 200°C , 300°C , keep 20 min
Roof sandstone	Li [24]	Xuzhou, China	/	18	$\Phi 50 \times 25$ mm	$\Phi 50$ mm SHPB test device	25°C , 800°C , $5^\circ\text{C}/\text{min}$, keep 1 h; impact load of 0.30, 0.35, 0.40, 0.45, 0.50, and 0.55 MPa
Sandstone	Li et al. [25]	China	/	12	$\Phi 50 \times 25$ mm	$\Phi 50$ mm SHPB test device	18.6 s^{-1} , 24.3 s^{-1} , 46.3 s^{-1} , 132.7 s^{-1}
Medium-grained sandstone	Liu and Xu [51]	Qinling, China	52% Qtz; 27% Cal; 8% Pl; 6% Kfs; 3% Ill; 2% Chl; 1% Mot; 1% Dol	35	$\Phi 100 \times 50$ mm	$\Phi 100$ mm SHPB test device	25, 100, 200, 400, 600, 800, and 1000°C ; keep 2 h; impact velocity of 11.0–15.0 m/s
Sandstone	Liu et al. [52]	China	/	18	$\Phi 50 \times 50$ mm	$\Phi 50$ mm SHPB test device	82 s^{-1} , 92 s^{-1} , 106 s^{-1} , 118 s^{-1} , 156 s^{-1} , 164 s^{-1}
Sandstone	lv et al. [53]	China	41% Qtz; 26% Cal; 17% Pl; 9% Kfs; 1% Talc; 2% Chl; 2% Ill; 1% Hem	12	$\Phi 97 \times 43$ mm	$\Phi 100$ mm SHPB test device	31.0 s^{-1} , 43.5 s^{-1} , 48.2 s^{-1} , 81.4 s^{-1}
Fine sandstone	Ma et al. [54]	Shanxi, China	/	20	$\Phi 50 \times 25$ mm	SHPB test device	25°C , 100°C , 200°C , 300°C
Sandstone	Mahanta et al. [55]	Rajasthan, India	80.2% Qtz; 7.3% Di; 6.8% Kln; 5.4% Cal; 0.4% Spl	/	$\Phi 50 \times 100$ mm	AG-X universal testing machine	25°C , 100°C , 200°C , 300°C , 500°C , 600°C , 800°C , 1000°C , $10^\circ\text{C}/\text{min}$, keep 3 h
Sandstone	Wang et al. [56]	Shaanxi, China	/	/	/	$\Phi 100$ mm SHPB test device	25°C , 100°C , 200°C , 400°C , 600°C , 700°C , 800°C , 900°C , $5^\circ\text{C}/\text{min}$, keep 3 h
Red sandstone	Wang et al. [57]	China	81% Qtz; 10% Pl; 3% Kfs; 3% Cal; Chl; Ill; Hem	6	$\Phi 96 \times 48$ mm	$\Phi 100$ mm SHPB test device	$1.5^\circ\text{C}/\text{min}$, 200°C , keep 4 h; $-2.25^\circ\text{C}/\text{min}$, water bath (20°C), keep 6 h; 0, 10, 20, 30, and 40 TS cycles
Siltstone	Yin et al. [58]	China	/	24	$\Phi 50 \times 30$ mm	$\Phi 50$ mm SHPB test device	25°C , 100°C , 200°C , 300°C , 400°C , $3.33^\circ\text{C}/\text{min}$, keep 2 h
Sandstone	Yin et al. [59]	China	/	25	$\Phi 50 \times 100$ mm	SHPB test device	25°C , 200°C , 400°C , 600°C , 800°C ; $3.33^\circ\text{C}/\text{min}$, keep 4 h
Sandstone	Zhu et al. [26]	China	/	15	$\Phi 50 \times 30$ mm	$\Phi 50$ mm SHPB test device	71.5 s^{-1} , 92.3 s^{-1} , 118.3 s^{-1} , 126.7 s^{-1}

Cal: calcite; Chl: chlorite; Di: dickite; Dol: dolomite; Hem: hematite; Ill: illite; Kfs: K-feldspar; Mot: montmorillonite; Op: opaque minerals; Pl: plagioclase; Qtz: quartz; Spl: spinel; Zeo: zeolite.

FIGURE 1: Stress-strain curve of brittle rock.

induced cracks, which affect its strength and integrity and brings great hidden dangers to engineering constructions. Therefore, it is necessary to understand the mechanical behavior of rock under different temperature conditions. On the other hand, underground engineering construction often involves ore and rock crushing, pile driving, explosives, and other engineering techniques, which are almost all related to fracturing and stress wave propagation in rocks under impact loads. This is related to the dynamic mechanical properties of rock.

At present, there has been much in-depth research on the influence of different temperatures and strain rates on the physical and mechanical properties of rocks. However, there are relatively few studies on the evaluation of rock brittleness under these two influencing factors. Based on this, this study selected sandstone as the research object and studied the effects of temperature and strain rate on the brittleness of sandstone.

2. Experimental Results of Previous Studies

In previous experiments, some researchers focused on the influences of tensile strength, mineral composition, and other factors on the brittleness of the specific rocks, while neglecting important common characteristics. In this paper, we summarized the effects of the strain rate and different treatment temperatures on the brittleness of sandstone based on the previous research results, as shown in Table 1. In these studies, sandstone is collected from different areas and processed into different sizes and then treated at different temperatures. With different loading rates, the impact load test or static compression test of sandstone treated at different temperatures was carried out with SHPB, and the stress-strain curves under different test conditions were obtained. In this paper, the brittleness of sandstone is quantitatively calculated according to these stress-strain curves, to explore the influence of temperature and strain rate on the brittleness of sandstone.

3. Methods of Calculating Rock Brittleness

After many years of theoretical exploration, researchers have put forward nearly 80 brittleness indexes (BI) of rock [13]. Because of differences in test conditions, some of these indexes can reflect differences in rock brittleness, while others need further experiments to verify their accuracy. In this study, based on stress-strain curves, two typical empirical formulas for evaluating rock BI are selected [14] (formulas (1) and (2)).

$$BI_1 = \frac{E}{M}, \quad (1)$$

where E is the prepeak elastic modulus and M is the postpeak elastic modulus.

$$BI_2 = \frac{W_{el}}{W_{tot}}, \quad (2)$$

where W_{el} is the elastic energy at failure and W_{tot} is the total energy at failure.

As shown in the stress-strain curve in Figure 1, BI_1 is approximately the ratio of the AB segment to the FG segment. BI_2 is equal to the ratio of the areas for CDE and OABCD in the stress-strain curve in Figure 1.

4. Analysis and Discussion

4.1. Influence of the Strain Rate. Figure 2 shows the relationship between the brittleness index and strain rate calculated by formulas (1) and (2). As shown in Figure 2(a), there is an overall increasing trend in BI_1 with an increasing strain rate. When the strain rate is lower than 100 s^{-1} , BI_1 slowly increases from 0.2 to about 0.7. When the strain rate is between 100 s^{-1} and 180 s^{-1} , BI_1 increases rapidly from 0.7 to about 2.5. As shown in Figure 2(b), BI_2 decreases with the increase in the strain rate. When the strain rate is lower

FIGURE 2: Changes in the BI of sandstone with strain rate. (a) BI₁ [25, 26, 51, 53]; (b) BI₂ [25, 26, 54, 60]; (c) BI₁ and BI₂ [58].

than $100 s^{-1}$, BI₁ decreases rapidly from 0.9 to about 0.7. When the strain rate is between $100 s^{-1}$ and $180 s^{-1}$, the BI₁ decreases slowly from 0.7 to about 0.65. At a higher strain rate, with the increase in the strain rate, BI₁ increases slowly, while BI₂ decreases rapidly, as shown in Figure 2(c).

4.2. Influence of Temperature. To facilitate the comparison of the variation of the brittleness index with temperature, the data for the calculated brittleness indexes from different

literature are standardized as shown in equation (3). The BI₁^{*} and BI₂^{*} denote the standardized brittleness indexes calculated in equations (1) and (2), respectively. Figure 3 shows the variation in the BI^{*} of sandstone with treatment temperature. It can be seen that under low-temperature conditions, BI₁^{*} and BI₂^{*} both shows a downward trend with increasing temperature, as shown in Figures 3(a) and 3(c). Under high-temperature conditions, BI₁^{*} and BI₂^{*} can be divided into two stages as the temperature increases, but they show

FIGURE 3: Changes in the BI^* of sandstone with temperature: (a, b) BI_1^* ; (c, d) BI_2^* . [38, 52, 55–57, 59, 61–63].

opposite trends. When the heating temperature is about $100^{\circ}C$, BI_1^* drops to the minimum and BI_2^* increases to the maximum, as shown in Figures 3(b) and 3(d).

$$BI^* = \frac{BI - BI_{\min}}{BI_{\max} - BI_{\min}}, \quad (3)$$

where BI^* represents the standardized brittleness index. BI represents the brittleness index at different temperatures, and $BI_{\max}$ and $BI_{\min}$ represent the maximum and minimum values of the brittleness index at different temperatures, respectively.

5. Discussion

Brittleness is a very important property of rocks (especially deep rocks). The brittleness of rock is affected by many factors such as mineral composition, Young's modulus, Poisson's ratio, compressive strength, and tensile strength [15–17]. In this paper, the effects of the strain rate and temperature on the brittleness of sandstone were studied and the mechanisms of influence were discussed.

The brittleness of rock is closely related to its failure stress. According to previous studies, the variation in failure stress with a strain rate of brittle materials is shown in Figure 4(a), which is roughly divided into three stages. Among them, point A is the end of stage I, and the

FIGURE 4: Variations in dynamic strength and dissipated energy with strain rate. (a) Failure stress with strain rate [22]. (b) DIF with strain rate [30, 64–68].

corresponding strain ϵ_1 is $10^2 s^{-1}$; point B is the inflection point of the stage II curve, and the corresponding strain ϵ_s is $10^3 s^{-1}$; and point C is the starting point of stage III, and the corresponding strain ϵ_2 is $10^4 s^{-1}$ [18]. In stage I, that is, in the area of low strain, a quasistatic fracture mainly occurs in rocks. The original pore closures and microcracks in sandstone are compressed and compacted with the increase in the strain rate, resulting in a slow increase in rock strength and brittleness [19]. This stage is mainly controlled by the thermoactivation mechanism [20, 21]. In stage II, with the continuous increase in the strain rate, the fracture damage controlled by dynamics in the sandstone gradually increases [22, 23], and the energy consumed gradually increases [24–26]. The energy required for crack generation is greater than the energy required for crack expansion [27]. In rock dynamics tests, due to the short duration of the impact loading action, the specimen does not have enough time for energy accumulation and can only be used for energy accumulation by increasing the strength of the rock [11, 28, 29]. The dynamic increase coefficient (DIF), which is the ratio of dynamic strength to static strength, is usually used to express the increase in rock strength [30], as shown in Figure 4(b). It can be seen that when $\log \epsilon$ is close to $2.0 s^{-1}$ ($\epsilon = 100 s^{-1}$), the DIF value increases significantly, which leads to a rapid increase in the brittleness of the rock. When the strain rate is close to $10^3 s^{-1}$ (point B), the failure stress growth rate reaches the maximum. In stage II, the macroviscosity mechanism is dominant [31], the inertia of the rock is gradually obvious, and the viscosity coefficient decreases

FIGURE 5: Schematic diagram of low-temperature freezing and high-temperature thermal damage to the rock.

with the increase in the strain rate. When the upper yield is reached in the shock compression process, that is, entering stage III, the rate of increase in rock strength with the increase in the strain rate slows down. With the continuous increase in the strain rate, the rock enters the high strain zone, and defects of different sizes begin to grow in the rock. The sandstone will produce permanent damage, and the rock will change from brittleness to ductility. The strain rates involved in this study includes stage I and a portion of stage II.

The temperature has a great influence on the physical and mechanical properties of sandstone [32]. Under low-temperature conditions, bulk water, capillary water, and adsorbed water in the rock gradually freeze into ice, and some of the unfrozen adsorbed water forms a water film (as shown in Figure 5) [33]. As the temperature continues to decrease,

FIGURE 6: Relationship between BI and strain rate and temperature [51, 69]: (a) variation in BI with the strain rate at different heat treatment temperatures; (b) 3-D variations of BI with the strain rate and temperature.

the thickness of the unfrozen water film becomes progressively thinner [34]. Due to the supporting force of the ice, the connection force between the mineral particles becomes stronger, and the mineral skeleton becomes more stable, which strengthens the strength of the rock [35]. At the same time, due to the rapid expansion of ice in the formation process, it squeezes the surrounding minerals and produces microcracks, weakening the mechanical properties of the rock [36]. According to the study of Wang et al. [37], during the freezing process of rock, the strengthening effect inhibits the weakening effect, which leads to the continuous increase in the strength of the rock. Therefore, the brittleness of the rock gradually increases as the temperature decreases [38], as shown in the low-temperature area in Figure 6(a). Under high-temperature conditions, due to the different thermal expansion coefficients of mineral particles [39], nonuniform expansion occurs and thermally induced cracks occur. At the same time, the adsorbed water and crystal water in the sandstone overflowed, causing the pore structure of the sandstone to change [40]. As the temperature continues to rise, different degrees of defects and cracks occur after the rock cools [41, 42]; especially after 400°C, thermal cracks are gradually obvious, and the internal microcracks of the sandstone increase, the strength decreases, and the brittleness is weakened, as shown in the high-temperature area in Figure 6(a). Around 600°C, quartz begins to undergo a phase transformation from α -quartz to β -quartz [43, 44], and the internal and intergranular cracks between the mineral particles become increasingly serious [45–47]. Under high temperatures, these changes in the internal structure of sandstone lead to a gradual decrease in its strength, reduced brittleness, and enhanced plasticity [48].

In summary, temperature and strain rate have significant effects on the brittleness and plasticity of sandstone due to its water content, pore and crack distribution, mineral struc-

ture, and so on. Low temperature and high strain rate are conducive to the enhancement of sandstone brittleness, as shown in Figure 6(b). Both BI_1 and BI_2 can reflect the brittleness of sandstone but have different applicable conditions. Within the strain rate range of this study, as the strain increases, the internal pores and cracks of the sandstone decrease and the strength of the sandstone increases. For the calculation of BI_1 , because the prepeak and postpeak elastic moduli are considered, the calculation result is more accurate. Under low-temperature conditions, the strength of sandstone increases, and the BI_1 and BI_2 changes show the same change trend. However, under high-temperature conditions, the plastic characteristics of sandstone are enhanced, which leads to the unreliable selection of the post-peak elastic modulus of some samples for BI_1 , so the BI_2 value is more reliable. At around 100°C, BI_2 suddenly increases, which may be due to the high-water content of sandstone. The water evaporates during the heat treatment process, and the original pores and cracks of the sandstone are exposed. When subjected to a load, the strain rate increases, increasing brittleness.

6. Conclusions

In this paper, based on existing research data, the variation in the brittleness of sandstone with temperature and strain rate was studied and discussed from a microscopic point of view. At the same time, the variation in sandstone brittleness under the combined action of temperature and strain rate was analyzed. The main conclusions are as follows:

- (1) Temperature and strain rate are two important parameters that affect the brittleness of sandstone. Based on previous studies, two empirical formulas

for the quantitative calculation of sandstone brittleness are selected. Among them, the BI_1 method is more accurate in calculating the variation in the sandstone brittleness index with the strain rate, while the BI_2 method is more accurate in calculating its variation with temperature

- (2) Under dynamic load, with the increase in the strain rate, the failure stress and brittleness of sandstone are positively correlated. When the strain rate exceeds 100 s^{-1} , the failure stress of sandstone begins to increase significantly, resulting in a significant increase in the brittleness index
- (3) Under low-temperature conditions, the water inside the rock gradually freezes into ice. Due to the strengthening effect of ice, the strength and brittleness of the rock increase. Under the condition of high temperature, the thermal damage to sandstone is intensified after 400°C , and the quartz phase changes after 600°C , which leads to the increase in microcrack density and the decrease in brittleness in sandstone. The conditions of low temperature and high strain rate are beneficial to the enhancement of sandstone brittleness

Notations

BI: Brittleness index
 BI^* : Standardized brittleness index
 E : Prepeak elastic modulus
 M : Postpeak elastic modulus
 W_{el} : Elastic energy and total energy at failure
 W_{tot} : Slab top surface temperature.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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