[Rock and Soil Mechanics](https://rocksoilmech.researchcommons.org/journal)

Volume 41 | Issue 3 Article 3

9-27-2020

# Experimental investigation of accelerated failure of creep rock induced by impact disturbance

Qing-yuan WANG
*Institute of Underground Space for Stability and Support of Surrounding Rock, Heze University, Heze, Shandong 274015, China*

Jie LIU
*Institute of Underground Space for Stability and Support of Surrounding Rock, Heze University, Heze, Shandong 274015, China*

Pei-tao WANG
*Key Laboratory of Ministry of Education for Efficient Mining and Safety of Metal Mine, University of Science and Technology Beijing, Beijing 100083, China*

Fei LIU
*Institute of Underground Space for Stability and Support of Surrounding Rock, Heze University, Heze, Shandong 274015, China*



## Custom Citation

WANG Qing-yuan, LIU Jie, WANG Pei-tao, LIU Fei, . Experimental investigation of accelerated failure of creep rock induced by impact disturbance[J]. Rock and Soil Mechanics, 2020, 41(3): 781-788.

Rock and Soil Mechanics 2020 41(3): 781−788 ISSN 1000−7598
https: //doi.org/10.16285/j.rsm.2019.5592 rocksoilmech.researchcommons.org/journal

# Experimental investigation of accelerated failure of creep rock induced by impact disturbance

WANG Qing-yuan[1], LIU Jie[1], WANG Pei-tao[2], LIU Fei[1]

1. Institute of Underground Space for Stability and Support of Surrounding Rock, Heze University, Heze, Shandong 274015, China
2. Key Laboratory of Ministry of Education for Efficient Mining and Safety of Metal Mine, University of Science and Technology Beijing, Beijing 100083, China

**Abstract:** Rockmass may be in a creep state for a long time during underground mining. The failure progress of surrounding rock mass may be accelerated due to the mining disturbance. The rockmass failure is usually later than the mining activities and shows an obvious time lag effect, which brings difficulty in predicting the occurrence of engineering disaster. Given this problem, impact-creep tests of rock specimens were conducted under multi-cycle drop weight using a rock rheology-impact test machine. The changing law of axial strain of sandstone specimens was analyzed. The influence of creep state, impact times of drop weight, and impact energy on the deformation and failure characteristics of creep rock were discussed. In terms of energy point of view, the failure rule of creep rock was explained under impact disturbance. The test results show that under the same rock creep state, the internal rock damage increases gradually with the increase of impact energy and impact times. The formation process of the damage zone was accelerated and the energy utilization rate was increased, which leads to the accelerated creep failure of rock samples. The impact disturbance causes the accumulated elastic strain energy within rock specimen to be released directionally along the damage zone and damage occurs. The research results provide a theoretical basis for the prediction of delayed rockburst disasters.

**Keywords:** mining disturbance; time-dependent effect; creep-damage; impact energy

## 1 Introduction

Rockburst is one of the major disasters in mining operations due to its strong destructive and the rockburst has always been a research challenge in rock mechanics and mine disaster prevention. As of the end of the year 2014, according to a statistic, there have been 147 mines that subject rockburst in China[1]. Thousands of casualties were recorded resulting from rockburst disaster during the year 2004–2014 alone[2]. The intensity and frequency of rockburst increase gradually as the increase of mining depth and in-situ stress.

It has been known that the mechanism of rockburst is extremely complicated. To illuminate the mechanism, different theories have been developed from different viewpoints by scholars from various countries[3−4]. In general, a widely accepted view is that the occurrence of rockburst is a process in which the concentrated high stress has reached the strength of coal rock mass. A necessary condition for the rockburst occurrence is the large amount of strain energy stored in the coal rock mass. The degradation of coal rock mass and thus the reduction of rock mass strength is a key factor for the rockburst due to the mining disturbances. It has been widely accepted that the combination effect of static and dynamic loading can induce rockburst[5]. Based on more and more in-filed observations and on-site engineering practices, however, rockburst often occurs only after a period of mining actives and shows an evident time lagging[6−8]. The time-lagging brings huge uncertainties and difficulties in accurate prediction and early warning of potential rockburst. Jiang et al[9] pointed out that the mining disturbance caused a ‘creep type’ rockburst in lieu of causing an ‘instant type’ rockburst directly. The rockburst, whether triggered directly by mining disturbance or induced behind the mining activities, must be closely related to the stress wave propagation and degradation of the coal rock masses due to the mining disturbance[10]. It is hence of great significance to understand rockburst mechanism by researching of mining disturbance with time lag effect.

Since Griggs (1939)[11] commenced the creep tests on limestone, shale, sandstone, etc., domestic and foreign scholars have been conducted a wide range of studies on the creep characteristics of rocks both in laboratory experiments and theories, and remarkable achievements have been obtained[12−14]. Through the rock creep test, different empirical creep equations are obtained, and a related creep theoretical model is then proposed, which is a common approach to study the rock creep behavior[15−16]. However, rock rheology is the concerned core of these experiential studies and the influence of dynamic disturbance on the rheological process is not considered. In recent years, some scholars have begun to pay attention to the issue of the time-lagging effect of the rockburst by mining disturbance. Xu et al[17] discussed the occurrence condition and lag time of ore pillar rockburst under the rheological rock strata. They proposed a theoretical explanation for the time lag phenomenon of rockburst and derived an equation of the rockburst lag time. Xu

Received: 28 March 2019 Revised: 29 July 2019
This work was supported by the National Natural Science Foundation of China (NSFC) (51604017) and the Doctoral Foundation of Heze University(XY16BS36).
First author: Wang Qing-yuan, male, born in 1984, associate Professor, mainly engaged in research on rock mechanics. E-mail: wqyan_2006@163.com

et al.[7] established a simple mechanical model and provided a criterion for the time lag type rockburst in terms of coal pillar rheology. A test facility was developed by Gao's research group[18−20] for studying the disturbance effect on rock rheological. The developed tester was used to conduct rheological tests on the coal and rock specimens under disturbance loading. Based on the test results, they proposed a series of concepts such as the ultimate rock strength and disturbance effect of rock rheological. Referring to the time lag issue of coal pillar rockburst, Yin et al[8] established a coal-roof deformation mechanical model and systematically studied the lag time issue of the isolated coal pillar rockburst. The stress waves, caused by the mining disturbance, propagate in a short period within rock masses. However, the creep damage of rock mass is in a long-time period. Although the time effect should be considered for both mining disturbance and rock creep, the time scales have a large difference between the creep and mining disturbance, which are the mechanical response of rock mass under two strain rates. It is therefore difficult to study the mining disturbance and rock creep within the same theoretical framework[21].

As discussed above, this study conducted a drop weight impact-creep test on rock specimens using a rock rheology-impact test machine. The influence of impact disturbance on the rock creep damage was studied and damage characteristics of rock specimens were analyzed. The mechanism of time lag effect was then revealed for the rockburst caused by mining disturbance, which could provide a theoretical basis for the prevention and control of time lag type rockburst induced by mining disturbance.

## 2 Impact-creep test

In this study, the green sandstone specimens were subjected to multiple cycles of dynamic impact using a rock rheology impact testing machine to obtain a deeper understanding of the deformation and failure rules of the rock creep under dynamic impact loading.

### 2.1 Specimen preparation

In general, the roof rock types of the coal seam is mostly sandstones and green sandstone is used as the test material in this study. To identify its mineral composition, composition analysis of rock specimens was conducted, and details can be found in Wang et al[22]. To eliminate the influence of sample discreteness on test results, the rock specimens were drilled out from the same large rock block. The dimension of the cylinder specimen was 50 mm (diameter) by 100 mm (height). The acoustic wave detection and screening tests were performed on the specimens after the processing procedure. Specimens with similar acoustic wave speed were selected for testing. Besides, the prepared specimens were stored in the laboratory without any external vibrations and ensured in a natural water-containing environment. Through laboratory tests of the green sandstone, basic physical and mechanical properties of the green sandstone specimens were determined, as shown in Table 1.

**Table 1 Physical and -mechanical properties of green sandstone**

| *UCS* /MPa | $\sigma_T$ /MPa | *E* /GPa | $\upsilon$ | *C* /MPa | $\rho$ /(g • cm$^{-3}$) |
|---|---|---|---|---|---|
| 29.8 | 2.4 | 8.4 | 0.29 | 6.2 | 2.17 |

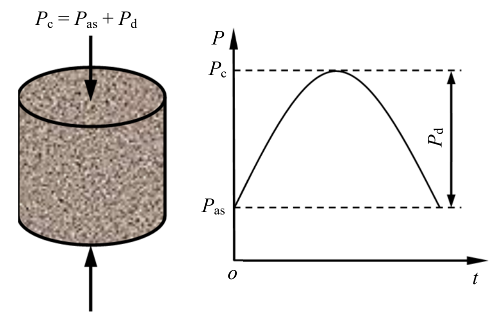
### 2.2 Test device

The impact-creep tests of the green sandstone were conducted using a rock rheology-impact test machine. The test device was described in detail in Wang et al[12] and there is no intent to go into detail herein. To sum, the test device consists of several systems such as an axial constant loading system, a temperature control system, a disturbance load application system, and a measurement system of deformation and load. A gravity loading method is adopted to keep a constant loading force for a long period. Six different drop weights were designed and processed, and different dynamic impact energy could be realized based on a different combination of the six drop weights. In addition, the strain and load measurement system are composed of a TST3827E static and dynamic signal tester, strain gauges attached to the rock surface, pressure sensor, laser displacement sensor, and computer.

To increase the loading force, a combination of pulley block and hydraulic cylinder with a various cross-sectional area is used in the test device system. Through a two-stage load increasing, the loading force should be increased by 80 times in theory. However, the actual increase extent of the load is smaller than that forms the theoretical value due to the friction effect. Based on the actual measurements, it is found that the multiple of the force increasing fluctuates in the range of 63–67 under different loading weights. The creep test requires higher long-term stability of the loading. To verify the stability of its loading system, a long-term stability test was conducted for the test device. For 98 hours testing period, the stress value fluctuated around 51.0 MPa with a load variation less than or equal to 0.3%, which should meet the requirements of the rock creep tests.

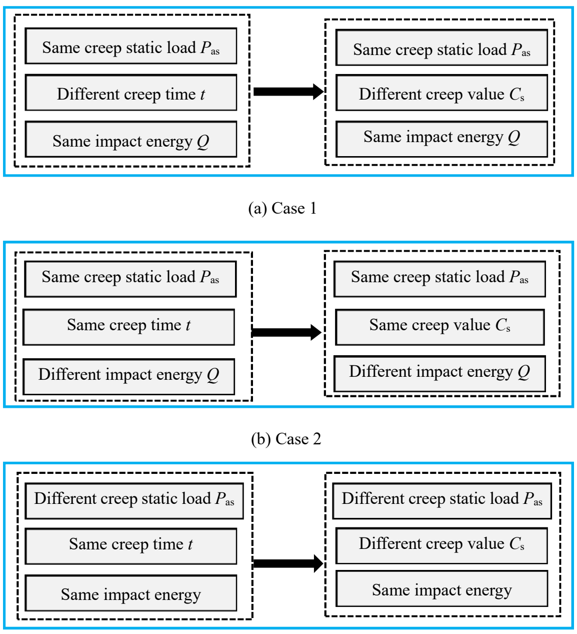
### 2.3 Test scheme

Like the one-dimensional coupled static–dynamic loading, the loading model of impact loading during rock creep can be represented in Fig.1. In Figure 1, $P_c$ is the total loading, $P_{as}$ is the axial creep static loading, $P_d$ is the axial impact loading. The impact load of rock creep-impact test is applied when the rock creep test reached to a certain time. During the weight impact, the rock creep state $C_s$, the creep static load $P_{as}$, and the impact energy $Q$ all have an influence on the behavior of the rock specimen. The rock creep state $C_s$ during the impact is determined by both the creep static load $P_{as}$ and the duration time $t$ of the creeping stage. Same $P_{as}$ and various $t$ and different $P_{as}$ and same $t$ could lead to the same rock creep value $C_s$ under the same impact, but the latter combination of $P_{as}$ and $t$ cannot be accurately controlled during the test and it is not considered in this study. To facilitate the analysis, only one variable is changed (i.e., Case 1 and Case 2) during the tests, as shown in Fig.2. Although only $P_{as}$ is different when at loading, for Case 3, the $C_s$ will not be the same within the same period during the impact loading. In this consideration, only Case 1 and Case 2 were selected to perform tests. According to Wang et al[22], the green sandstone specimens were not failed after 120 hours under a static creep loading of 20 MPa. Again, Case 1 and Case 2 were selected to conduct the tests.




(a) Rock loading (b) Stress-time curve

**Fig.1 Schematic diagram of the coupled creep rock dynamic impact disturbance loading**




(a) Case 1

(b) Case 2

(c) Case 3

**Fig.2 Loading conditions of creep-impact test**

Case 1: Same $P_{as}$, different $t$, same $Q$.

Under Case 1, the $C_s$ is different while the $P_{as}$ and $Q$ are the same under the impact loading. Under the static creep load of 20 MPa, the green sandstones were firstly subjected to the creep tests of 12, 24, and 60 hours, and then the drop weight impacting was conducted to the specimens. The static creep load was kept constant during the impact loading with a drop weight of 10 kg. During the multiple cyclic impacts, the drop weight was released freely from a height of 20 cm, which corresponding to impact energy of 20 J. The impact loading was repeated until the green sandstone was failed if the specimen did not fail at the previous impacting. The time interval between the two adjacent impacts was set as 60 s.

Case 2: Same $P_{as}$, same $t$, different $Q$.

Under Case 2, the $Q$ is different while the $C_s$ and $P_{as}$ are the same under the impact loading. Under the static creep load of 20 MPa, the green sandstones were firstly subjected to the creep tests of 12 hours, and then the impacting was conducted to the specimens. The $P_{as}$ was kept constant during the impact loading and the drop weight is still 10 kg. During the multiple cyclic impacts, the drop weight was released freely from heights of 10, 20, 30 cm, which corresponding to impact energy of 10, 20, 30 J. Like the Case 1, the impact loading was repeated until the sandstone was failed if the specimen did not fail at the previous impacting. The time interval between two adjacent impacts was 60 s.

## 3 Test result analysis

Figure 3 shows the multiple cycle impact test results of green sandstone under Case 1 and Case 2. Based on the test curves of the creeping rock under drop weight impacting tests, the changing law between the axial and lateral cumulative strains and the impact numbers are analyzed. The relations between the impact number and the strain and energy prior to the impact are also explored in the following.

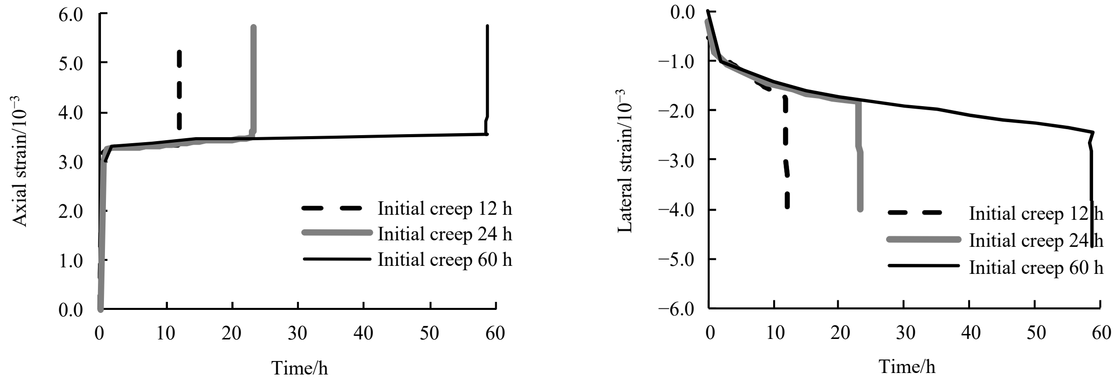
### 3.1 Strain change

Figure 3(a) presents the strain–time curves of green sandstone subjected to multiple impacts of 20 J with different creep times (12, 24, 60 hours) under initial creep stress of 20 MPa. It is seen from Fig.3(a) that under the same creep static load, different creep strains of rock specimen are observed at different creep times. When the initial creep times are 12, 24, and 60 hours, the axial/lateral strains of the green sandstone are $3.325\times10^{-3}/1.680\times10^{-3}$, $3.450\times10^{-3}/1.900\times10^{-3}$, and $3.550\times10^{-3}/2.200\times10^{-3}$, respectively. Compared with the axial strain changes, the lateral strain shows a relatively high value and is more sensitive to the stress. The impact disturbance has a profound influence on the rock damage. The impact load accelerates the creeping damage of the rock, which accelerates the creep stage of the rock specimen from constant velocity creep stage to the accelerate creep stage. This change will induce the

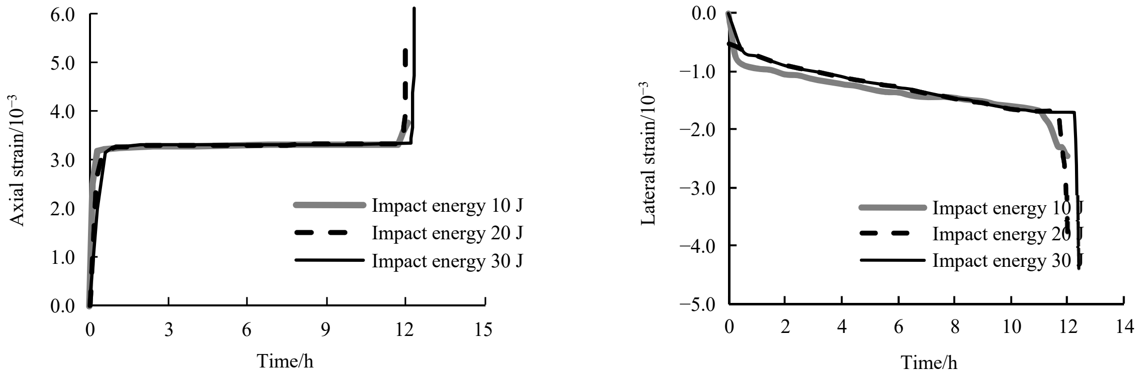
Rock and Soil Mechanics, Vol. 41 [2020], Iss. 3, Art. 3



rock damage. Under the same creep static load and same creep time, as shown in Fig.3(b), it is seen that the lateral and axial strains are basically the same between different rock specimens. A similar creep effect is observed for both rock specimens. In this case, the green sandstone specimens subject different cumulative strains under different impact energies.




(a) Case 1: strain-time curves under different creep times




(b) Case 2: strain-time curves under different impact energies

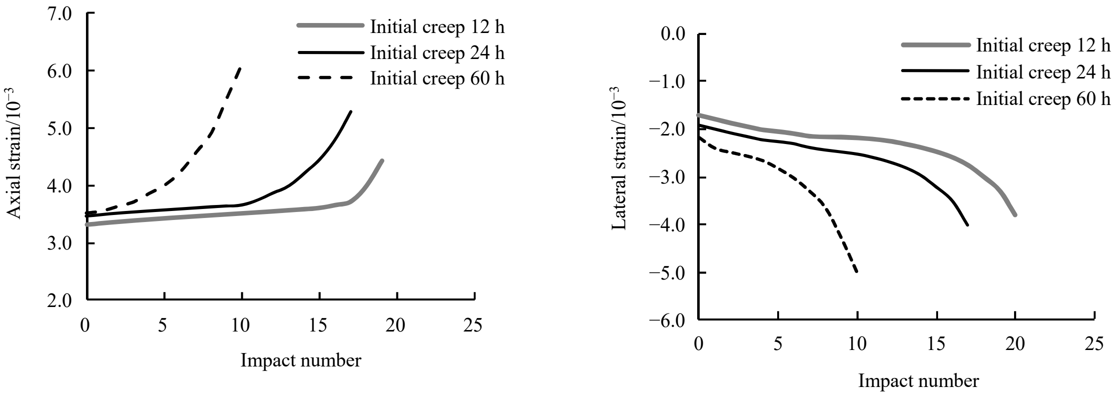
**Fig.3 Strain-time curves of creep-impact test**

Figure 4 shows the relationships between the cumulative axial and lateral strains and the impact numbers under Case 1 and Case 2. It is seen from Fig.4 that the axial and lateral strains increase gradually as the increase of the impact numbers. The increasing extent reaches the maximum prior to the rock failure. The trends are different between the axial and lateral deformations under the impact disturbances. The variations of axial strain do not show an obvious change after being impacted. With the increase of the impact numbers, a rapid increase of axial strain is observed before the rock failure. For the lateral strain change, a relatively stable increasing rate is observed after being impacted, and the response to the impact loading is more pronounced than that of the axial strain.

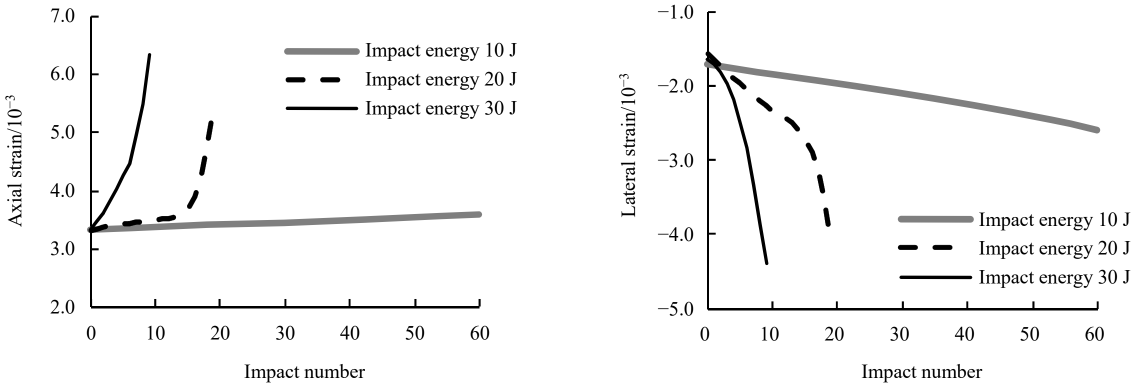
After 12 hours of creep time and then subjected to impact energy of 20 J, Figure 5 presents the transient axial strain fluctuation curves at different impact times under a stress level of 20 MPa. It is seen from Fig.5 that the green sandstone specimen failed after 20 impacts under this condition. It can also be seen from the figure that the strain of the selected four impacts experienced an instantaneous increase and then decreased rapidly, and then increased slowly as the time increases. Corresponding to the four impact times, the instantaneous increasing strains are $4.8\times10^{-5}$, $5.7\times10^{-5}$, $6.5\times10^{-5}$, and $8.7\times10^{-5}$, respectively. The increased extent of the strain shows a small change. When compared the strain increasing extent of the four impact moments, it is observed that the magnitude of the sudden decrease in strain followed by the impact becomes smaller as the impact number increases. This observation is because, at the beginning of the impact, there are only a few areas within the rock that show damage due to short creep time and low stress levels. At this stage, the rock specimen can be viewed as an elastic body. Once the drop weight impacted the specimen, an instantaneous strain increase occurs and the strain is then returned to the original strain level, which is resulted from the elastic rebound effect. As the increase of the impact numbers, the accumulation of damage within the rock becomes large and the rock cannot be considered as an elastic body anymore, which results in the partial recovery of the instantaneous strain after the

https://rocksoilmech.researchcommons.org/journal/vol41/iss3/3
DOI: 10.16285/j.rsm.2019.5592

drop weight impact on the rock. Between two adjacent impacts, the strength of rock reduces due to the impact that causes damage to the rock and thus changes the mechanical properties of the rock. Under the same creep stress condition, the creep strain formed between two adjacent impacts becomes larger and larger as the impact time increases.




(a) Case 1: strain vs impact number curves under different creep times




(b) Case 2: strain vs impact number curves under different impact energies

**Fig.4 Curves of impact number and accumulation strain**

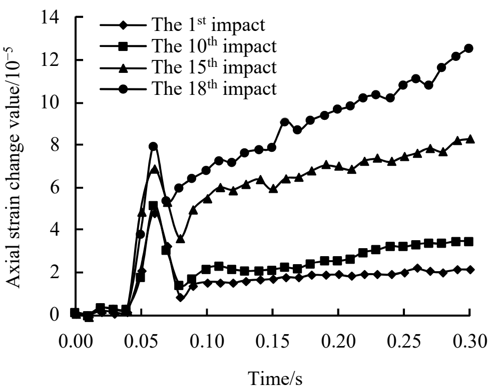



**Fig.5 Axial strain change under different impact times**

### 3.2 Impact numbers

As shown in Fig.4(a), with the increase of the strain before the impact, the required impact numbers of rock failure decrease. For instance, the impact numbers are 20, 17, and 10 times corresponding to the 12, 24, and 60 hours of initial creep time. Before the impact, the development of initial creep deformation changes the rock mechanical properties, which is manifested as a hardening in the axial direction and softening degradation in the lateral direction. The larger the strain of rock specimen before impact, the more damage is generated inside the rock, and the lower resistance capacity to damage when the rock is subjected to an impact loading. The impact numbers decrease with the increase of the strain before the impact when the rock specimen is subjected to an impact loading.

Figure 6 gives the impact numbers for failing the green sandstone specimens at various impact energies under the Case 2 scenario. From Fig.4(b), it is seen that the green sandstone specimen did not fail after 60 impacts when the impact energy is 10 J. When the impact energy is increased to 20 and 30 J, the required impact times reduced to 20 and 8 times to fail the rock specimen, respectively. In general, the greater the impact energy, the fewer the impact numbers that required to fail the rock specimen. This relation can be expressed by the following equation:

$$N = a\mathrm{e}^{-bU_{\mathrm{di}}} \tag{1}$$

where $N$ is the impact number when the rock specimen fails; $U_{\mathrm{di}}$ is the single impact energy of the drop weight; $a$ and $b$ are the constants related to the impact energy.

When the rock specimen is subjected to an impact load, the impact numbers decrease exponentially as the impact energy increases. If the impact energy is not high enough, which may not have an obvious influence on the rock specimen. Only when the impact energy reaches to a certain value, the residual strain of rock specimen will be caused due to the impact loading. In such a case, the rock specimen can be failed after a certain number of impacts. When the impact energy is 10 J and the green sandstone is subjected to 60 impacts, the axial strain of the rock specimen is only $3.0\times10^{-4}$ and without failure.

Equation (2) can be used to uniformly express the relationship between the impact numbers and the impact energy and strain prior to the impact when the rock specimen failed:

$$N = f\left(\varepsilon_0, U_{\mathrm{di}}\right) \tag{2}$$

where $\varepsilon_0$ is the strain value prior to impact. When the impact energy is constant, a function relation can be derived between the impact number and strain before the impact. The impact number required for rock failure decreases rapidly as the increase of the strain prior to the impact. At the same time, the strain prior to the impact is affected by loading stress and creep time. Under the same loading stress and creep time, the impact number required for rock failure decreases rapidly as the impact energy increases.

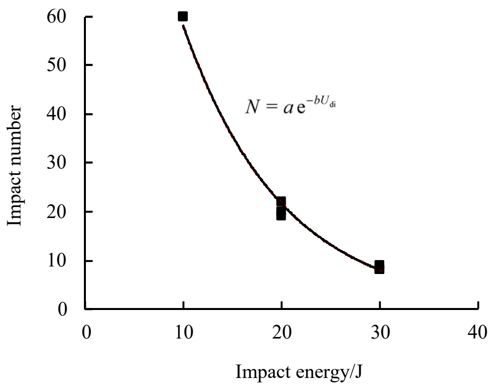



**Fig.6 Relationship between impact number and impact energy**

### 3.3 Energy analysis

The rock deformation and failure process are an irreversible process of energy dissipation. Based on the law of thermodynamics, energy conversion is an essential feature of the matter physical process. The influence of the external load on the rock is not only in the changes of the stress-strain state, but also partially consumed within the rock, which leads to the changes of rock damage state. Considering the rock deformation under the external force and assuming no heat exchange between the physical process and the outside, and the total input energy generated by the external force work is $U$, according to the first law of thermodynamics, it can be obtained as[24]

$$U = U_{\mathrm{d}} + U_{\mathrm{e}} \tag{3}$$

where $U_{\mathrm{d}}$ is unit dissipation energy; $U_{\mathrm{e}}$ is the unit release elastic strain energy.

During the rock creep process under drop weight impact, there are two parts of the external force (creep stress and impact disturbance) that work on the rock specimen. Suppose the work done by the two forces are $U_{\mathrm{c}}$ and $U_{\mathrm{dy}}$. When the work done by the two parts on the rock exceeds the work $U$ that required for the rock uniaxial compression failure, the rock specimen is then destabilized and failed.

$$U_{\mathrm{c}} + U_{\mathrm{dy}} \geqslant U \tag{4}$$

$U_{\mathrm{c}}$ can be obtained according to the integral of the load and creep deformation curve during the creeping stage:

$$U_{\mathrm{c}} = \int_L F\mathrm{d}L \tag{5}$$

where $F$ is the load; $L$ is the rock deformation.

$U_{\mathrm{dy}}$ can be expressed as follows:

$$U_{\mathrm{dy}} = \sum_i^N U_{\mathrm{di}}\eta_{\mathrm{i}} \tag{6}$$

where $\eta_{\mathrm{i}}$ is the effective utilization rate of each impact energy, which denotes the ratio of rock absorbed energy used to damage rock to the incident energy during the impact process.

According to Xie et al[25], as the incident energy increases, the total energy of the transmission and reflection increases. However, the total energy of the transmission and reflection tend to a stable value as the incident energy increases continually. When the incident energy reaches a very high level, the extent of energy absorbed increases gradually and it increases rapidly after reaching a certain level. The absorbed energy is the source to damage the rock specimen. The greater the impact energy, the higher the effective utilization rate $\eta_{\mathrm{i}}$ of the impact energy. Under the same impact energy, the effective utilization rate $\eta_{\mathrm{i}}$ of impact energy also increases gradually as the increase of the impact numbers.

To facilitate the test and measurement, equation (6) can be re-written as follows:

$$U_{\mathrm{dy}} = U_{\mathrm{di}} \times N \times \overline{\eta} \tag{7}$$

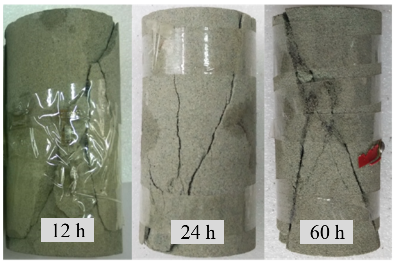
where $\overline{\eta}$ is defined as the average utilization rate of the impact energy.

Based on the equation (7), the average utilization rate of impact energy is calculated under the conditions of Case 1 and Case 2, as shown in Table 2. It can be seen from Table 2 that for Case 1 scenario, as the creep deformation of the initial creep stage increases, the average utilization rate of impact energy increases from 1.48% to 2.55% under the same impact energy. For Case 2 scenario, under the same initial creep state, the average utilization rate of impact energy increases from 1.48% to 2.47% under the same increasing extent of the impact energy. The average utilization of impact energy increases, which indicates the internal damage of rock specimen increases as the increase of the impact numbers and eventually leads to the failure of the rock specimen.

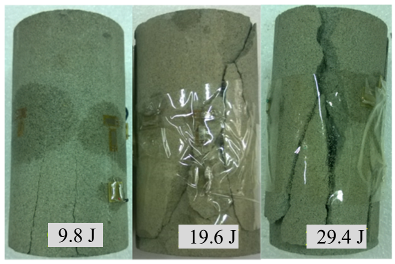
**Table 2 Average utilization of impact energy**

| Working condition | Creep stress / MPa | Creep time / h | Creep energy / J | Impact energy / J | Impact number $N$ | Average energy utilization $\bar{\eta}$ /% |
|---|---|---|---|---|---|---|
| | 20.0 | 11.8 | 6.63 | 19.60 | 20 | 1.48 |
| Case 1 | 20.0 | 23.1 | 7.07 | 19.60 | 16 | 1.72 |
| | 19.6 | 57.8 | 7.45 | 19.60 | 10 | 2.55 |
| | 19.8 | 11.9 | 6.59 | 9.80 | 60 | — |
| Case 2 | 20.0 | 11.8 | 6.63 | 19.60 | 20 | 1.48 |
| | 19.9 | 12.2 | 6.65 | 29.40 | 8 | 2.47 |

Figure 7 presents the failure modes of the impact creep for green sandstone specimens under Case 1 and Case 2. It is seen that, in general, the shear failure mode is the main failure mode for the green sandstone specimen. The fragmentation degree shows somewhat different when the creep time and impact energy are different. According to equation (3), the work done by the external force on the rock specimen will be converted into the dissipative energy and the releasable elastic strain energy of the rock unit. Under the effect of external load, the rock unit damage is increased and thus the rock strength is reduced. When the releasable strain energy of the rock unit reaches to the energy required for rock unit failure, the rock unit is failed. In such a manner, the rock specimen is totally failed when a certain number of the load-bearing rock units failed instantaneously. Under the effect of impact load, a large amount of elastic strain energy is stored in a short time. When the stored strain energy exceeds the rock unit's surface energy, it will cause the instantaneous failure of the rock unit and will lead to the rock fragmentation phenomenon. When the impact load is relatively small or without being impacted, relatively lower releasable elastic strain energy is stored in the rock unit. As the increasing of the loading time, the number of failed rock units increases gradually, and thus the rock strength decreases. When the relatively less releasable stored elastic strain energy exceeds the rock unit's surface energy and because of the less releasable stored elastic strain energy, an approximate static failure is found for the rock specimen, which breaks into several large pieces of rock block.




(a) Case 1




(b) Case 2

**Fig.7 Failure modes of impact creep for green sandstone specimens under two test conditions**

## 4 Conclusions

The number of impacts required for rock failure is related to the impact energy and the strain value before the impact. The impact number decreases exponentially with the impact energy increase. As the increase of the strain prior to the impact, the impact number of rock failure decreases rapidly.

The impact disturbance accelerates the creep damage of the rock, which accelerates the creeping stage of the rock specimen from constant velocity creep to the accelerated creep stage. This change will cause the rock failure. The research results provide a theoretical basis for the time lag of mining-induced rockburst.

## References

[1] PAN Yi-shan, LI Zhong-hua, ZHANG Meng-tao. Distribution, type, mechanism and prevention of rockbrust in China[J]. Chinese Journal of Rock Mechanics and Engineering, 2003, 22(11): 1844–1851.

[2] JIANG Yao-dong, ZHAO Yi-xin. State of the art: investigation on mechanism, forecast and control of coal bumps in China[J]. Chinese Journal of Rock Mechanics and Engineering, 2015, 34(11): 2188–2204.

[3] QI Qing-xin, LI Xiao-lu, ZHAO Shan-kun. Theory and practices on stress control of mine pressure bumping[J]. Coal Science and Technology, 2013, 41(6): 1–5.

[4] JIANG Fu-xing, LIU Yi, YANG Wei-li, et al. Relationship between rock burst and the three zonestructure loading model in Yuncheng coal mine[J]. Journal of Mining & Safety Engineering, 2017, 34(3): 405–410.

[5] JIANG Yao-dong, PAN Yi-shan, JIANG Fu-xing, et al. State of the art review on mechanism and prevention of coal bumps in China[J]. Journal of China Coal Society, 2014, 39(2): 205–213.

[6] XU Si-peng, MIAO Xie-xing. Advance of study on time effect of rockburst[J]. Mining safety & environmental protection, 2001, 28(2): 27–29.

[7] XU Si-peng, ZHONG Wei-ping, JIA Feng-su. Study on the time effect of rock burst for a pillar[J]. Ground Pressure and Strata Control, 2001(1): 75–77.

[8] YIN Wan-lei, PAN Yi-shan, LI Zhong-hua, et al. An improvement and comparative analysis of shear lag warping displacement function in thin-walled box girder[J]. Chinese journal of applied mechanics, 2016, 33(6): 1106–1112.

[9] JIANG Fu-xing, FENG Yu, KOUAME K J A, et al. Mechanism of creep-induced rock burst in extra-thick coal seam under high ground stress[J]. Chinese Journal of Geotechnical Engineering, 2015, 37(10): 1762–1768.

[10] JIANG Fu-xing, WANG Yu-xiao, LI Ming, et al. Mechanism of rockburst occurring in protected coal seam induced by coal pillar of protective coal seam[J]. Chinese Journal of Geotechnical Engineering, 2017, 39(9): 1689–1696.

[11] GRIGGS D T. Creep of rocks[J]. Journal of Geology, 1939, 47: 225–251.

[12] WANG Q Y, ZHU W C, XU T, et al. Numerical Simulation of Rock Creep Behavior with a Damage-Based Constitutive Law[J]. International Journal of Geomechanics, 2016: 04016044.

[13] HEAP M J, BAUD P, MEREDITH P G, et al. Time-dependent brittle creep in Darley Dale sandstone[J]. Journal of Geophysical Research: Atmospheres, 2009: 114(B07203), 1–22.

[14] BRANTUT N, HEAP M J, BAUD P, et al. Rate- and strain-dependent brittle deformation of rocks[J]. Journal of Geophysical Research: Solid Earth, 2014: 119, 1818–1836.

[15] ZHANG Ming, BI Zhong-wei, YANG Qiang, et al. Creep test and rheological model selection of marble of Jinping I hydropower station[J]. Chinese Journal of Rock Mechanics and Engineering, 2010, 29(8): 1530–1537.

[16] ZHANG Yu, XU Wei-ya, WANG Wei, et al. Study of rheological tests and its parameters identification of soft rock in fractured belt[J]. Chinese Journal of Rock Mechanics and Engineering, 2014, 33(Suppl.2): 3412–3420.

[17] XU Zeng-he, LI Hong, XU Xiao-he. The occurrence condition and the hysteresis time for the rockburst of the ore pillar under the rheological rock seam[J]. West-China Exploration Engineering, 1996, 8(2): 26–30.

[18] GAO Yan-fa, MA Peng-peng, HUANG Wan-peng, et al. RRTS–II testing machine for rock rheological perturbation effect[J]. Chinese Journal of Rock Mechanics and Engineering, 2011(2): 238–243.

[19] GAO Yan-fa, XIAO Hua-qiang, WANG Bo, et al. A rheological test of sandstone with perturbation effect and its constitutive relationship study[J]. Chinese Journal of Rock Mechanics and Engineering, 2008, 27(Suppl.1): 3180–3185.

[20] WANG Bo, GAO Chang-yan, CHEN Xue-xi, et al. Axial load test study on the perturbation properties of rock rheology[J]. Journal of China Coal Society, 2017, 42(6): 1443–1450.

[21] WANG Qing-yuan. Uniaxial compression creep behavior of green sandstone subjected to dynamic disturbance of drop weight hammer[D]. Shenyang: Northeastern University, 2016.

[22] WANG Qing-yuan, ZHU Wan-cheng, LIU Hong-lei, et al. Size effect of long-term strength of sandstone under uniaxial compression[J]. Rock and Soil Mechanics, 2016, 37(4): 981–990.

[23] LI Xi-bing, GONG Feng-qiang, ZHAO J, et al. Test study of impact failure of rock subjected to one dimensional coupled static and dynamic loads[J]. Chinese Journal of Rock Mechanics and Engineering, 2010, 29(2): 251–260.

[24] XIE He-ping, JU Yang, LI Li-yun. Criteria for strength and structural failure of rocks based on energy dissipation and energy release principles[J]. Chinese Journal of Rock Mechanics and Engineering, 2005, 24(17): 3003–3010.

[25] XIE He-ping, PENG Rui-dong, JU Yang, et al. On energy analysis of rock failure[J]. Chinese Journal of Rock Mechanics and Engineering, 2005, 24(15): 2603–2608.