Study on Dynamic Mechanical Properties of Limestone Under Impact Loading

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Abstract. In order to study the variation of the mechanical properties of limestone under the condition of impact load, the dynamic mechanical properties of limestone under different strain rate and cyclic impact conditions were studied. The results show that the uniaxial compressive strength of limestone is 93.76MPa and the acoustic velocity is 5122m·s⁻¹, and under the condition of single impact load, the peak stress and strain rate are positively correlated. The peak strain increases with the increase of strain rate, and the larger the strain rate, the more serious the fragmentation of limestone. Under the condition of cyclic impact load, the cumulative damage of limestone increases gradually, and the more impact times, the faster the increase speed.

1. Introduction
In the process of blasting construction, the length of the fracture surface will increase continuously under the action of frequent blasting, and even penetrate, forming the main crack, and finally unstable, and this process is called cumulative damage Effect. Holcomb [1] et al carried out a large number of indoor tests, found that the rock has a significant memory effect. The nonlinear stress-strain characteristics of soft rock under triaxial cyclic load are studied [2]. The variation characteristics of the internal microcracks of granite under uniaxial cyclic load were studied by Akesson [3]. Gatelier [4] et al. took sandstone as a transverse anisotropic body and studied its damage change rule under multiple static cyclic uniaxial loads. Ray [5] et al. studied the uniaxial compressive strength of the Chunar sandstone at different cycle times.

With the continuous improvement of numerical simulation technology, the research on the damage of surrounding rock caused by blasting is no longer limited to theoretical derivation, laboratory test and field test, and there are many research results of numerical simulation. Sauang [6] et al. introduced the mohr-coulomb model, adopted programming, and studied the change rules of blasting impact cumulative damage, damage range and related parameters of rock mass strength with ANSYS-DYNAa. L.Oriard [7, 8] et al. studied the damage change rule of surrounding rock after repeated blasting load based on the field measurement in the actual project. F.e.haeuze [9] proposed and studied the expansion effect of rock joints.

The damage characteristics under static, single impact and different cyclic impact loads are studied in this paper. The aging damage model proposed by our research group is verified according to the measured data. Based on this model, the cumulative damage of limestone after repeated impact cycles...
is deduced, and the damage threshold range of limestone resulting in cracks and failure and loss of bearing capacity is pointed out.

1.1. Study on static mechanics of limestone

In order to reduce the workload and reduce the test error, the limestone of the same section is used for the bulk rock samples. The DW2-170 water drill is used for the field sampling first. Multi-function high-precision cutting machine and high precision grinding machine was adopted to process sample to φ50mmx100mm and φ75mmx50mm.

Single-axis compression test (sample encoding of SY1-1, SY1-2, SY1-3) was performed on 3 limestone specimens at the hydraulic servo laboratory of the Mining (Beijing) Institute of Mechanics and Architectural engineering, as shown in Figure 1.

![Figure 1. Total stress and strain curve of limestone](image)

As you know from Figure 1, at the beginning of loading, because of the limestone itself there are cracks, pores and other bad structural surface, cracks, pores closed, limestone is mainly axial deformation. With the increase of load, the internal fissures and pores of the specimen are basically completely closed, the axial strain and transverse strain are linearly increased, and the volume strain is linearly related to the load when the specimen enters the elastic stage. As the load continues to increase, the radial strain change rate increases and the specimen enters the expansion failure stage. After the peak, the specimen is damaged dramatically. Elastic modulus E and Poisson's ratio are detailed in table 1.

| Category | Compressive strength /MPa | Peak strain/10^-3 | E/GPa | Poisson's ratio | Acoustic velocity/(m·s^-1) |
|----------|---------------------------|------------------|-------|----------------|------------------------|
| SY1-1    | 93.27                     | 7.41             | 21.79 | 0.251          | 5117                   |
| SY1-2    | 98.85                     | 7.11             | 20.12 | 0.261          | 5096                   |
| SY1-3    | 89.16                     | 7.43             | 23.97 | 0.267          | 5155                   |
| Average  | 93.76                     | 7.32             | 21.96 | 0.26           | 5122                   |

2. Study on dynamic mechanical properties of limestone under single impact

The experiment was carried out in the state key laboratory of deep geotechnical mechanics and underground engineering, China university of mining and technology (Beijing). The basic principle of
SHPB test is the theory of elastic stress wave propagation in slender bar. There are two basic assumptions: the plane assumption, that is, in the process of stress wave propagation in slender bar, each cross section of the bar stays in the plane state. Stress uniformity hypothesis, that is, the stress in the specimen is equal everywhere in the process of stress wave propagation.

Liquid nitrogen was used to pressurise the gun bore. When the required pressure was reached, liquid nitrogen was released and the bullet hit the incident bar at a certain speed. When the stress wave propagated forward in the incident bar to the surface of the sample, reflection and transmission occurred. Incident wave $\varepsilon_i$, reflection wave $\varepsilon_r$ and transmitted wave $\varepsilon_t$ are recorded by means of transient waveform memory.

The stress, strain rate and strain of limestone specimen are calculated by formula (1), (2), (3):

$$\sigma = \frac{E (\varepsilon_i + \varepsilon_r + \varepsilon_t) A}{2 A_s}$$

$$\dot{\varepsilon} = \frac{(\varepsilon_i - \varepsilon_r - \varepsilon_t) C}{l_s}$$

$$\varepsilon(t) = \int_0^t \dot{\varepsilon} \, d\tau$$

Where $A, A_s$ is the cross-sectional areas of the compression bar and sample; $l_s$ represents the thickness of the sample; $C$ is the elastic wave velocity in the pressure bar; $E$ is the elastic modulus of the steel bar; $\varepsilon_i, \varepsilon_r$ and $\varepsilon_t$ represent the incident strain, reflected strain, and transmitted strain of the bars, respectively.

According to the calibration coefficient obtained, combined with equations (1), (2) and (3), the full stress-strain curve of limestone sample can be obtained, as shown in figure 2. The test data are shown in table 2.

![Figure 2. Test curves under different strain rate conditions](image)

As shown in figure 2 and table 2, when the strain rate is 72.36 s$^{-1}$, the peak stress is 118.75MPa and the peak strain is 0.00245, and the peak stress, peak strain and maximum strain increase obviously with the increase of impact velocity or the increase of strain rate. When the strain rate is 163.47 s$^{-1}$, the peak stress is up to 405.69MPa and the peak strain is 0.01172. This is mainly due to: under the impact load, especially when the impact speed is large (the strain rate is large), the limestone itself is static, due to inertial action, its lateral deformation is "constrained", it will become more and more obvious
with the increase of impact speed, equivalent to the application of "confining pressure" in limestone samples. This confining pressure increases with the increase of the impact velocity, that is, the limestone is in the triaxial compression state under the action of impact load, therefore, the peak stress and peak strain of limestone increase correspondingly when the impact velocity is large (the strain rate is large).

As can be seen from figure 2, for the test data, when the impact velocity is lower than 7.72 m·s⁻¹, the strain rate is less than 111.62 s⁻¹, the limestone has good linear elasticity, and the plastic section before the peak strain is short. With the increase of strain rate, the plastic section before the peak stress increases significantly. This is mainly because when the strain rate is large, the limestone reaches the uniaxial compressive strength of limestone in a relatively short time. For this test, the strain rate is large, and the full stress-strain curve of limestone is mainly divided into four stages: linear elastic stage, crack growth and development stage, crack rapid development stage and unloading stage.

According to the data in table 2, the correlation between the strain rate and the impact velocity of the incident bar and between the strain rate and the peak stress was studied, as shown in figure 3 and 4.

### Table 2. Test data

| Category | Incident bar speed/(m·s⁻¹) | Average strain rate/(s⁻¹) | Peak stress/MPa | Peak strain/10⁻³ | Failure morphology |
|----------|--------------------------|--------------------------|----------------|------------------|--------------------|
| DSY1-1   | 5.23                     | 72.36                    | 118.75         | 2.45             | Complete           |
| DSY1-2   | 6.11                     | 86.73                    | 135.66         | 3.23             | Crack              |
| DSY1-3   | 6.86                     | 93.65                    | 158.19         | 3.93             | Crack              |
| DSY1-4   | 7.72                     | 111.62                   | 185.36         | 5.34             | Crack              |
| DSY1-5   | 8.63                     | 118.33                   | 256.71         | 6.11             | Destroy into chunks |
| DSY1-6   | 9.22                     | 135.52                   | 342.28         | 7.29             | Destroy for small chunks |
| DSY1-7   | 10.49                    | 163.47                   | 405.69         | 11.72            | Broken             |

![Figure 3. Fitting curve of strain rate and impact velocity](image)
It can be seen from figure 3 that when the impact velocity is 5.23 m·s⁻¹, the strain rate is 72.36 s⁻¹, and when the impact velocity is 7.72 m·s⁻¹, the strain rate is 111.62 s⁻¹, which is 1.54 times of the original. When the impact velocity is 10.49 m·s⁻¹, the strain rate is 163.47 s⁻¹, which is 2.26 times. According to the fitting of the measured data, the impact velocity increases linearly with the increase of strain rate, and the correlation coefficient is 0.987, indicating that the two have a good linear correlation.

\[
\dot{\varepsilon} = 16.71v - 17.87 \quad (R^2 = 0.974) \tag{4}
\]

\[
\sigma = 430.31\exp(\dot{\varepsilon} / 216.19) - 489.85 \quad (R^2 = 0.932) \tag{5}
\]

The impact failure morphology of limestone is analyzed, and the failure pattern under different strain rate conditions is shown in figure 8.

![Figure 4. Fitting curve of peak stress and strain rate of limestone](image)

![Figure 5. Failure morphology of limestone under different strain rate conditions](image)
As can be seen from figure 5, when the strain rate is 86.73s⁻¹, the limestone will crack; With the increase of strain rate, when the strain rate is 118.33s⁻¹, the limestone failure is 3 pieces. When the strain rate is 135.52s⁻¹, the limestone failure is 4 chunks and some debris. When the strain rate is 163.47s⁻¹, the limestone is relatively broken and there is almost no chunk limestone. The energy required for the formation of new cracks in the rock is larger than that for the propagation of the old cracks in the interior. From the energy point of view, when the impact velocity is small, that is, the strain rate is small and the incident energy is small, the limestone failure is dominated by the expansion failure of weak structural planes such as internal fissures and pores, so when the strain rate is low, the fracture fragmentation of limestone is larger. When the strain rate is high, the incident energy is large and the impact time is very short, so the weak structural surfaces such as the old cracks in the limestone specimen do not have time to expand, and new cracks occur in the limestone under the condition of extremely high incident energy, and then, The new and old cracks in limestone propagate rapidly under the action of external forces and form nuclei until they are subjected to external forces.

3. Study on dynamic mechanical characteristics of limestone under cyclic impact

According to the calibration coefficient obtained, combined with equations (1), (2) and (3), the full stress-strain curve of limestone sample can be obtained, as shown in figure 6. The test data are shown in table 3.

![Figure 6. Cyclic impact constitutive curve](image)

| Impact times | Incident bar speed/(m·s⁻¹) | Average strain rate/(s⁻¹) | Peak stress/MPa | Peak strain/10⁻³ | Failure morphology | Acoustic velocity/(m·s⁻¹) |
|--------------|-----------------------------|---------------------------|-----------------|-----------------|-------------------|--------------------------|
| 0            | -                           | -                         | -               | -               | Complete          | 5128                     |
| 1            | 5.29                        | 70.67                     | 111.34          | 2.94            | Complete          | 4934                     |
| 2            | 5.92                        | 85.26                     | 122.36          | 3.32            | Complete          | 4582                     |
| 3            | 5.44                        | 72.35                     | 95.61           | 4.42            | Crack             | 3512                     |
| 4            | 5.86                        | 73.69                     | 92.33           | 4.49            | Broken            | -                        |

It can be seen from figure 6 that under the first impact load, the limestone sample is complete, the peak stress is 111.34Mpa, the acoustic velocity decreases 194m·s⁻¹, and the damage is 0.074. At the second impact, due to the large impact velocity, the peak stress is greater than the peak pressure at the first impact, and the acoustic velocity decreases by 352m·s⁻¹, and the damage is 0.202. At the third impact, the limestone sample produced cracks, with a peak stress of 95.61Mpa, a
peak strain of 0.00442, a decrease in acoustic velocity of 1070 m·s⁻¹, and a damage of 0.531. At the fourth impact, the limestone sample was destroyed. It can be found that when the impact velocity is similar, the peak stress and acoustic velocity of the sample decrease with the increase of impact times, while the peak strain increases with the increase of impact times.

In order to study the damage characteristics of limestone under cyclic impact load, the compressional wave velocity of limestone after each impact was tested. In order to increase the coupling effect, vaseline was applied on the test section, and the RSM-SY5 acoustic wave tester was used to measure the acoustic velocity and obtain the damage factor. According to the measured data of 5 cyclic impacts of limestone, and by substituting the parameters obtained in table 4 into the formula (5) and (11) in literature [10], the variation law of limestone damage with strain after each impact can be obtained. As shown in figure 7.

**Table 4. Constitutive parameters of limestone fitting under cyclic load condition**

| Impact times | Strain rate/s⁻¹ | α/10⁻³ | m     | E₁/10⁶ | E₂     | η     | K     | Correlation coefficient |
|--------------|-----------------|--------|-------|--------|--------|-------|-------|-------------------------|
| 1            | 70.67           | 3.01   | 5.22169 | 10.64  | 398.086 | 70.67 | 10    | 0.979                   |
| 2            | 85.26           | 4.451  | 4.6535 | 7.027  | 338.1  | 100   | 10    | 0.923                   |
| 3            | 72.35           | 4.401  | 2.693  | 4.128  | 253.106| 100   | 10    | 0.973                   |
| 4            | 73.69           | 4.495  | 1.625  | 4.698  | 254.53 | 100   | 10    | 0.979                   |

**Figure 7. Constitutive fitting curve of limestone under cyclic shock**

It can be seen from figure 7 that in the four impact tests, the theoretical damage at the initial stage is basically zero, indicating that the limestone directly enters the linear elastic stage under the impact load. At the first impact, the theoretical damage of limestone increases when the strain is 0.000124. When the strain is between 0.000124 and 0.00164, the damage increases slowly. When the strain is 0.00164, the damage is only 0.00103. When the strain is between 0.00164 and 0.0025, the growth rate of theoretical damage of limestone increases. When the strain is close to the peak, the theoretical damage of limestone increases rapidly until the end of stress wave action, and the theoretical damage of sample is 0.225. At the second, third and fourth shocks, the maximum theoretical damages were 0.486, 0.673 and 0.959, respectively. It indicates that with the increase of impact times, the theoretical damage increases gradually, and the damage growth rate also increases. The theoretical damage threshold of limestone crack is within the range of 0.486–0.673, and the theoretical damage threshold of failure is greater than 0.673. Combined with the measured damage in table 3, it can be seen that the test damage threshold of limestone crack is within the range of 0.202–0.531, and the damage threshold of failure is greater than 0.531.
4. Conclusion
Static and dynamic mechanical tests were carried out with hydraulic servo system and SHPB test system, respectively. The dynamic strength factor of limestone under different impact velocity, cumulative damage under cyclic impact load and dynamic mechanical characteristics were studied. The following conclusions have been reached:

1. The uniaxial compressive strength of limestone is 93.76MPa and the acoustic velocity is 5122m·s⁻¹, and under the condition of single impact load, the peak stress and strain rate are positively correlated. The peak strain increases with the increase of strain rate, and the larger the strain rate, the more serious the fragmentation of limestone.

2. Under the condition of cyclic impact load, the cumulative damage of limestone increases gradually, and the more impact times, the faster the increase speed. The test damage threshold of limestone crack is within the range of 0.202~0.531, and the damage threshold of failure is greater than 0.531.

Acknowledgments
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