

Research Article

Energy Analysis Method for Uniaxial Compression Test of Sandstone under Static and Quasi-Dynamic Loading Rates

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Received 29 March 2021; Accepted 31 May 2021; Published 15 June 2021

Academic Editor: Xianjie Hao

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To investigate the energy evolution characteristics of sandstone under static-quasi-dynamic loading rates (1.0×10^{-3} , 5.0×10^{-3} , 1.0×10^{-2} , 5.0×10^{-2} , and 1.0×10^{-1} mm/s), the uniaxial compression tests, the uniaxial cyclic loading-unloading tests, and the uniaxial incrementally cyclic loading-unloading tests were conducted under five different loading rates. Through analysis of the elastic energy of the uniaxial cyclic loading-unloading test and the uniaxial incremental cyclic loading-unloading test, show that the impact of the loading rate and the cycle numbers on the elastic energy is less. Hence, we can deem that when the loads of the uniaxial incremental cyclic loading-unloading test and the uniaxial compression test are equal, the elastic energy of the two also equals. The energy in the uniaxial compression tests analyzed by the uniaxial incrementally cyclic loading-unloading test show that elastic energy increased linearly when the input energy increased under different loading rates. Through the linear energy storage law and the uniaxial incremental cyclic loading and unloading test, it is possible to analyze the energy in the uniaxial compression test at any loading rates. The results show that the greater the loading rate, the greater the peak elastic energy and peak input energy. But when the load is equal, the greater the loading rate, the smaller the input energy and elastic energy. Compared with traditional methods, the new energy analysis method is accurate and simple. Meanwhile, based on energy dissipation, the damage of rock during uniaxial compression tests was studied.

1. Introduction

Rock is a heterogeneous structure composed of solid phase, liquid phase, and gas phase. There are many natural defects with random distribution. Due to the complex internal structure of the rock, elastoplastic mechanics or fracture mechanics cannot better describe the process of rock failure [1]. The process of rock failure is essentially an energy transfer and exchange event, and the energy-related characteristics are significant in describing the mechanical properties of rock materials [2].

From the energy point of view, the analysis and research on the characteristics of rocks have attracted attention to

engineering and theoretical circles. In the theoretical study of the energy evolution of rocks, the strength criterion and the overall failure criterion are usually established based on the energy release and dissipation of rocks [3, 4]. Wang et al. [5] studied the quantification of the damage degree by the energy in the process of rock failure and analyzed the energy dissipation and energy conversion modes and the stress-energy mechanism that caused rock failure under cyclic loading-unloading. The results show that the characteristics of hard rock are infinitesimal deformation and sudden failure. Also, they established the stress-energy-rigid-damage multicriteria model of hard rock. Xu et al. [6] constructed an ore pillar-rock beam support system in the

plastic zone in order to ensure safe production in the gypsum mine area, analyzed the evolution of ore pillar and rock beams from the energy point of view, and obtained the instability judgment conditions related to the support system. Li et al. [7] used the dissipated energy as irreversible to derive the equivalent strain and damage yield criterion of elastic damage and established a model.

In terms of experimental analysis, Zhang and Goa [8] studied the energy evolution of rocks under uniaxial incrementally cyclic loading-unloading tests. The results show that the elastic energy and dissipation energy of the rock changes nonlinearly with loading stress. Zhang et al. [9] discussed the confidence in determining energy evolution characteristics and distribution relations through triaxial cyclic loading-unloading compression tests. Zhang et al. [10] proposed an energy analysis method to calculate the triaxial compression test. Kang et al. [11] studied the failure of granite at loading rates of 0.005, 0.01, and 0.05 mm/s from the energy point of view. The results show that the elastic strain energy and the scattered strain energy absorbed in the initial compression stage are relatively small. In the elastic stage, it mainly stored the elastic energy; the increased rate of the dissipated energy is less than the total energy and elastic energy.

Regarding the study of the elastic energy in the uniaxial compression test of rock under different loading rates, it is calculated by the elastic modulus [12]. From the rock cyclic loading and unloading curve, it is known that there is a hysteretic effect in the unloading process of the rock [13]. In other words, the unloaded stress-strain is a curve, so the calculated energy evolution law has a deviation. When the load is equal, the elastic energy of sandstone is almost unchanged under different cycles and loading rates. Using the uniaxial staged loading-unloading test combined with the linear energy storage law to analyze the energy evolution in the uniaxial compression tests. The study of the law of energy evolution in rock uniaxial compression tests under different loading rates is of positive significance to topics such as the energy mechanism of rock failure and rock bursts in mines.

2. Experimental Study

2.1. Rock Specimens. All tests in this paper use sandstone. The sandstone specimen is shown in Figure 1. Sandstone is from the same place of origin and has a similar internal structure. The height (H) of the sandstone specimens was 100 mm, and the diameter (D) was 50 mm. The sides and end faces of the rock specimens were slippery before testing. The tests on sandstone specimens were all carried out with an RMT-150B testing system. The tests on the sandstone specimen all carried out with the RMT-150B testing system.

2.2. Test Schemes. The tests on sandstone specimens were all carried out with an RMT-150B testing system. To study the influence of loading rates on energy evolution, conduct uniaxial compression test, uniaxial cyclic loading-unloading tests, and uniaxial incrementally cyclic loading-unloading tests on the sandstone specimen under different loading rates. Liang et al. [14] divided the static and quasi-dynamic

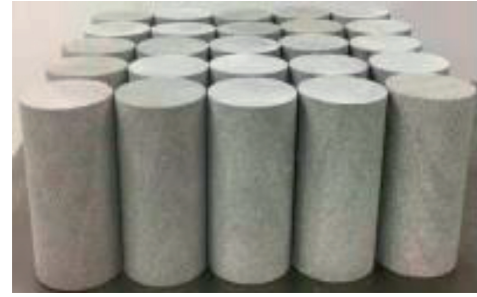


FIGURE 1: Sandstone specimens.

test loading conditions as follows. The strain rate is less than $5 \times 10^{-4} \text{ s}^{-1}$ for static loading and $5 \times 10^{-4} \text{ s}^{-1}$ to 10^2 s^{-1} for quasi-dynamic loading. Due to the limitations of the testing machine, this paper adopts the deformation rates' control loading method. The loading rates of the uniaxial compression test are 1.0×10^{-3} , 5.0×10^{-3} , 1.0×10^{-2} , 5.0×10^{-2} , and $1.0 \times 10^{-1} \text{ mm/s}$, corresponding to the static and quasi-dynamic loading rate range. The loading rate of the uniaxial compression test specimens U1, U2, and U3 is $1.0 \times 10^{-3} \text{ mm/s}$. The loading rate of the specimens U4, U5, and U6 is $5.0 \times 10^{-3} \text{ mm/s}$. The loading rate of the specimens U7, U8, and U9 is $1.0 \times 10^{-2} \text{ mm/s}$. The loading rate of specimens U10, U11, and U12 is $5.0 \times 10^{-2} \text{ mm/s}$. The loading rate of specimens U13, U14, and U15 is $1.0 \times 10^{-1} \text{ mm/s}$. The uniaxial cyclic loading-unloading rate is $5.0 \times 10^{-2} \text{ mm/s}$, and the upper limit of the cyclic loading and unloading of each specimen is 10 kN, 20 kN, 30 kN, 40 kN, 50 kN, 60 kN, and 70 kN, respectively.

The loading rates of uniaxial incrementally cyclic loading-unloading tests are 1.0×10^{-3} , 5.0×10^{-3} , 1.0×10^{-2} , 5.0×10^{-2} , and $1.0 \times 10^{-1} \text{ mm/s}$. 10 kN is a cycle, until the specimen is ruptured and, that is, the loading is carried out in the order of $0 \rightarrow 10 \rightarrow 0 \rightarrow 20 \rightarrow 0 \rightarrow 30 \text{ kN}$.

Since the output data of the rock mechanics testing system RMT-150B is load (kN) and deformation (mm), in order to facilitate analysis, the curves in this article are all axial load-deformation curve. The energy density and energy of the rock are used to describe the energy evolution of it. The energy density is calculated by using the stress-strain curve, which represents the energy per unit volume. The energy is calculated from the load-deformation. For the ease of analysis, energy (J) was used to describe the energy evolution of rocks in this paper.

3. Axial Load-Deformation Curve of Sandstone

3.1. Uniaxial Compression Curve of Sandstone. Figure 2 shows the axial load-deformation curve of sandstone under different loading rates. In the figure, a1, a2, and a3 are the deformation entering the elastic stage, the plastic stage, and the peak under a loading rate of $1 \times 10^{-2} \text{ mm/s}$. Under different loading rates, the rock has a compaction stage, elastic stage, plastic stage, and postpeak failure stage. During the compaction stage, the sandstone is compaction, and the

input energy transforms into elastic energy and dissipation energy. The energy stored in the rock is elastic energy. The energy dissipation caused by the friction between the original cracks of the compacted is called the dissipated energy [12]. Since the compaction stage is the compaction of the microcracks inside the rock, the total energy input is not much different, and the axial load-deformation curve is a performance of an aspect of the thermodynamic state, and the curve evolution trend is closer. The function of the compaction stage is the compaction of the microcracks inside the rock. The total energy input is not much different. The axial load-deformation curve is one performance of the thermodynamic state [15], so the curve evolution trend is closer under different loading rates. As the loading increases, sandstone enters the elastic stage, mainly elastic deformation, and produces a small number of microcracks. The smaller the loading rate, the more the original cracks and new cracks in the rock make friction and the more the energy dissipated. Therefore, after entering the elastic stage, the axial load-deformation curves under different loading rates of the rock deviate from each other to a certain extent. When the load further increases, the rock enters the plastic stage, a large number of new cracks are generated, and the original cracks grow. The lower the loading rate is, the more the friction between the rock cracks is sufficient and the more energy dissipated, and the degree of deviation between the uniaxial compression curves under different loading rates further increases. Part of the work done by the external loading on the rock mass is converted into dissipated energy, which gradually reduces its strength. The lower the loading rate is, the more sufficient the friction between rock cracks is, and more energy consumption under the same load. Therefore, the lower the loading rate, the lower the uniaxial compressive strength of the rock.

3.2. Uniaxial Cycle Loading-Unloading Curve. Figure 3 shows the axial load-deformation curve of the uniaxial cyclic loading-unloading test of sandstone, and the loading rate is 1.0×10^{-2} mm/s. The upper limit of the load is 10 kN; 20 kN is corresponding to the compaction stage. The residual deformation caused by the first loading and unloading of the uniaxial cyclic loading and unloading test is, respectively, 0.055 mm and 0.093 mm. The growth rate of the residual deformation is relatively fast. The increase in plastic deformation of sandstone is relatively tiny, and the deformation is mainly elastic. Therefore, the upper limit value of the loading is 30 kN, 40 kN, and 50 kN in the uniaxial cyclic loading-unloading tests for the first time. The plastic deformation is 0.173 mm, 0.183 mm, and 0.194 mm, and the deformation growth rate is relatively tiny. The plastic deformation of the first loading and unloading of the uniaxial cyclic loading-unloading test with the upper limit of the loading of 50 kN, 60 kN, and 70 kN is 0.194 mm, 0.229 mm, and 0.313 mm, respectively. Compared with the elastic deformation stage, the residual deformation growth rate increases significantly with the loading. After the first loading and unloading, the sandstone continues to be subjected to cyclic loading and unloading, and its residual deformation shows a decreasing trend.

Figure 4 shows the uniaxial incrementally cyclic loading-unloading tests' curves of sandstone under different loading rates. When the loading rate is 1×10^{-3} , 5×10^{-3} , 1×10^{-2} , 5×10^{-2} , and 1×10^{-1} mm/s, the sandstone strength is 66.3 kN, 69 kN, 77 kN, 79.1 kN, and 80.1 kN. The bearing capacity of sandstone under uniaxial incrementally cyclic loading-unloading tests is higher than uniaxial compressive strength. Many studies have shown that the bearing capacity of the rock will increase after a few times of loading and unloading; the rocks occurred in hardening, and the peak intensity increased after an additional loading. For example, You and Su's [16] studies on marble and Zuo Jianping's [17] studies on coal and rock mass show that the load-bearing capacity of samples is improving after a few loading and unloading actions. Combined with rock hardening [16, 17], under external load, stress concentration will occur at the original cracks inside the rock, resulting in large deformations and even local failures at the contact points. The debris formed at the stress concentration may fall off during unloading and fill the nearby voids, which improves the friction characteristics and the rock bearing capacity.

4. Sandstone Elastic in Uniaxial Cycle Loading-Unloading Tests

4.1. Influence of Cyclic Number on Elastic. By observing the uniaxial cycle loading-unloading curve, it is a discovery that the area under the unloading curve of the addition of sandstones has no significant change, and the area under the unloading curve is the elasticity of the rock. Liu et al. [18] studied the elastic energy of sandstone under uniaxial cyclic loading-unloading tests. The result shows that rock elastic energy remains unchanged under the constant cyclic load.

Figure 5 shows the elastic energy-cycle number curves of sandstone. The elastic energy of sandstone under cyclic loading-unloading has tiny fluctuations, and the overall direction is approximately parallel to the axis of the cycle number. The elastic energy of maximum change amplitude of uniaxial cyclic loading-unloading for each is 0.3782 J, which is relatively tiny. Therefore, it is regarded that the elastic energy of sandstone remains unchanged under the action of uniaxial cyclic loading-unloading tests. In the uniaxial cyclic loading-unloading tests of the rock with a constant upper load limit, with the cycle numbers' increases, the fatigue damage is on a rise, and the strength of the rock decreases. The uniaxial incrementally loading-unloading of the rock strengthens the bearing capacity related to friction, not the material strength. However, multiple cycles cause the gradual deterioration of material strength and periodic deformation causes fatigue damage [19].

4.2. The Effect of Loading Rates on Elastic Energy. To explore the elastic energy evolution law of sandstone under different loading rates, the elastic energy of each unloading point of uniaxial incrementally loading-unloading tests of sandstone was studied. The specimen numbers T1, T2, T3, T4, and T5 correspond to loading rates of 1.0×10^{-3} , 5.0×10^{-3} ,

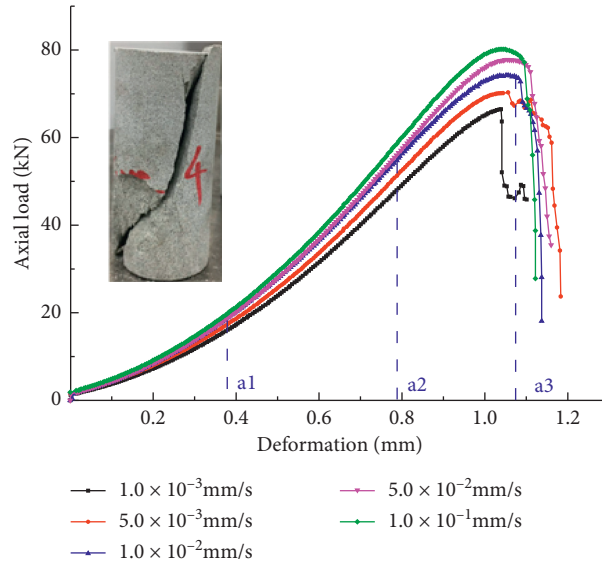


FIGURE 2: Axial load-deformation curves at different loading rates.

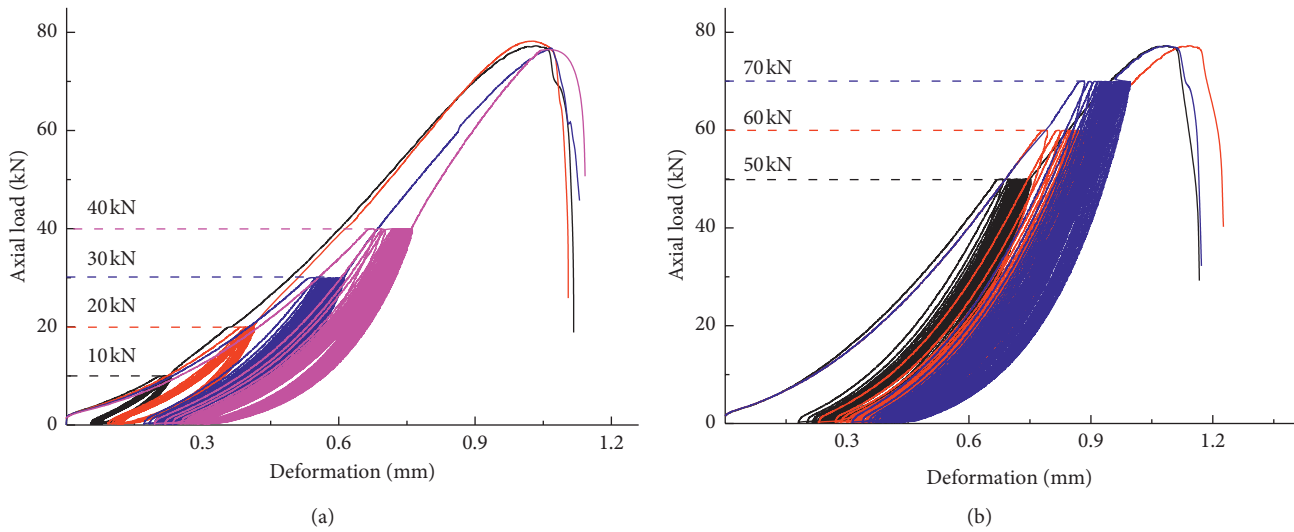


FIGURE 3: Uniaxial cyclic loading and unloading curve. (a) 10 kN–40 kN uniaxial cyclic loading-unloading curve. (b) 50 kN–70 kN uniaxial cyclic loading-unloading curve.

1.0×10^{-2} , 5.0×10^{-2} , and 1.0×10^{-1} mm/s, respectively, uniaxial incrementally loading-unloading tests. The elastic energy of each unloading point of uniaxial incrementally loading-unloading tests is showing in Table 1.

Figure 6 shows the evolution of elastic energy curves of sandstone. Compare the elastic energy of the uniaxial incremental cyclic loading-unloading test of rock under different loading rates with the first loading-unloading elastic energy of the uniaxial cyclic loading-unloading test of rock. When a load of rock is equal, the loading rates have a microeffect on its elastic performance. Based on the study of the evolution law of rock elastic energy, it can deem to that when uniaxial compression tests and uniaxial incrementally loading-unloading tests have the same load, regardless of whether the loading rates are equal and the elastic energy of the two is equivalence.

5. Sandstone Uniaxial Compression Energy Analysis under Different Loading Rates

5.1. The Linear Energy Storage Law of Sandstone. Based on the conclusion that the elastic energy is not affected by the loading rate and the cycle numbers, the uniaxial grading loading-unloading tests can analyze the energy evolution at the same load in uniaxial compression.

Table 2 shows the energy of uniaxial compression tests of sandstone under different loading rates. Using the law of elastic energy evolution, we can get the energy evolution of equal load at each unloading point of uniaxial compression and uniaxial incrementally loading-unloading tests. However, uniaxial incrementally loading-unloading tests can only analyze the energy evolution under specific loads in the uniaxial compression test. Gong et al. [20–22] obtained the linear energy storage law

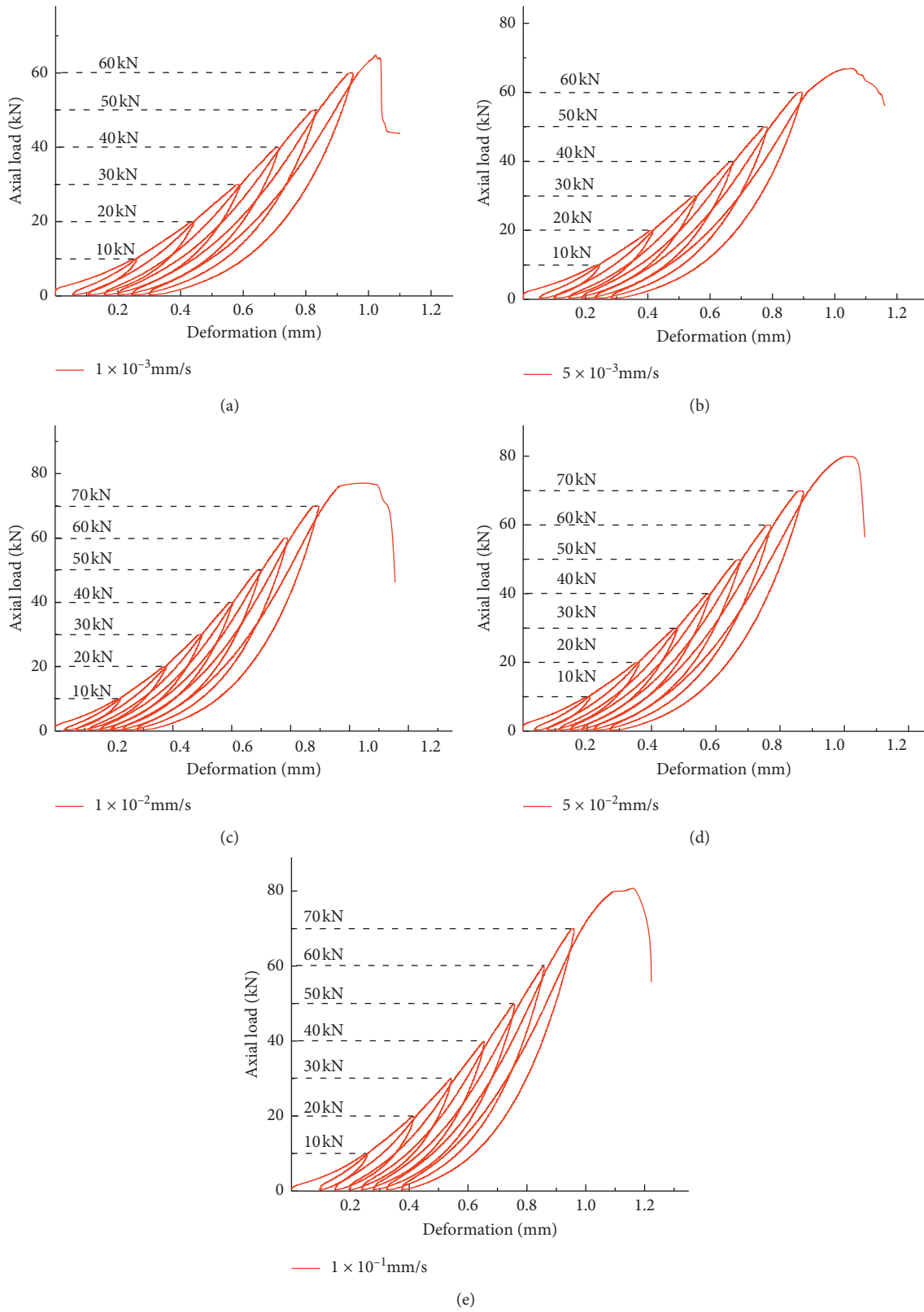


FIGURE 4: Uniaxial incrementally cyclic loading-unloading tests. (a) Specimen with loading rate of $1 \times 10^{-3} \text{ mm/s}$. (b) Specimen with loading rate of $5 \times 10^{-3} \text{ mm/s}$. (c) Specimen with loading rate of $1 \times 10^{-2} \text{ mm/s}$. (d) Specimen with loading rate of $5 \times 10^{-2} \text{ mm/s}$. (e) Specimen with loading rate of $1 \times 10^{-1} \text{ mm/s}$.

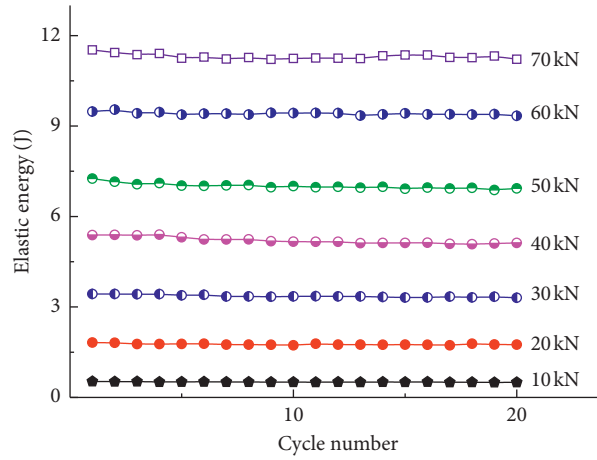


FIGURE 5: Elastic energy-cycle number curve.

TABLE 1: Energy evolution law of uniaxial incrementally loading-unloading tests.

Load (kN)	Loading rates (mm/s)									
	1.0×10^{-3} (Specimen T1)		Elastic energy (J)		1.0×10^{-2} (Specimen T3)		5.0×10^{-2} (Specimen T4)		1.0×10^{-1} (Specimen T5)	
	Elastic energy (J)	Input energy (J)	Elastic energy (J)	Input energy (J)	Elastic energy (J)	Input energy (J)	Elastic energy (J)	Input energy (J)	Elastic energy (J)	Input energy (J)
10	0.5336	1.3542	0.5283	1.2421	0.5347	1.2415	0.5432	1.2641	0.5406	1.2124
20	1.7882	3.0105	1.7981	2.9894	1.8063	3.2947	1.7941	3.0474	1.8023	2.8142
30	3.3095	6.3963	3.3124	6.2854	3.3009	6.0781	3.3376	5.7264	3.3100	5.2241
40	5.3120	10.0936	5.3214	9.5662	5.3421	9.2872	5.3845	9.0275	5.4011	8.4547
50	7.1032	14.6541	7.1842	14.0355	7.1891	13.4601	7.2064	13.0073	7.2219	12.4678
60	9.3945	19.1239	9.3867	18.5455	9.4167	17.8934	9.4054	17.0645	9.3972	16.1347
70	—	—	—	—	11.4427	22.5211	11.4210	21.8534	11.4348	20.3556

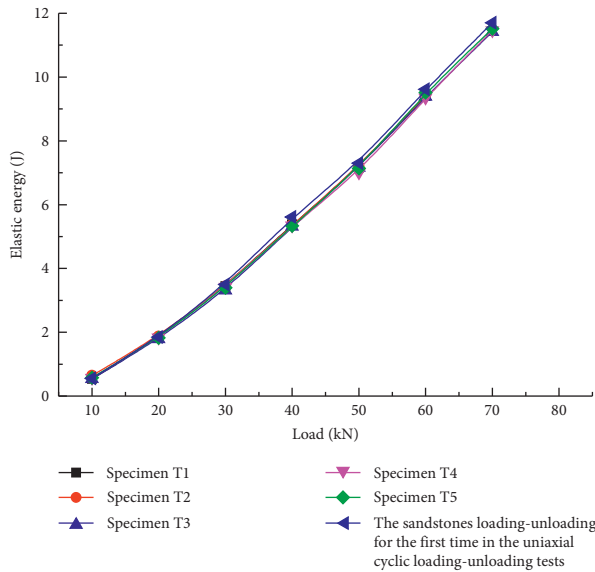


FIGURE 6: Evolution of elastic energy.

based on considering the energy consumption characteristics during the whole process of rock loading; the elastic energy and the total energy have a linear relationship during uniaxial compression tests, and its expression is

$$u^e = a_1 u + b_1. \quad (1)$$

u^e represents the energy density, and u represents the input energy density. Both a_1 and b_1 are fitting parameters.

This article is the utilization of energy to describe the energy variation law of the rock, and the product of energy density and volume is equal to the energy of rock. In consequence, the linear energy storage law is written as

$$U^e = aU + b, \quad (2)$$

where U^e is the elastic energy stored in the rock under any load, U is the specimen storage corresponding to U^e input energy, and both a and b are fitting parameters.

Table 3 shows the linear energy storage fitting formula under the static-quasi-dynamic loading rate. The analysis found that the energy evolution in the uniaxial compression test with different loading rates obeys the linear energy storage law. The energy evolution analysis can be performed on uniaxial compression tests at any loading rate, using the uniaxial incrementally loading-unloading tests and linear energy storage laws. A new method of energy evolution analysis for the uniaxial compression test of rock under different loading rates is proposed.

TABLE 2: Energy of uniaxial compression tests of sandstone under different loading rates.

Load (kN)	Elastic energy (J)	Input energy (J)					
		Loading rates 1.0×10^{-3} mm/s			Loading rates 5.0×10^{-3} mm/s		
		U1	U2	U3	U5	U6	U8
10	0.5336	1.3320	1.3211	1.3223	1.2367	1.2384	1.2312
20	1.7882	4.0105	4.0412	4.1324	3.8740	3.9113	3.9156
30	3.3095	7.3963	7.3623	7.4532	7.2965	7.2534	7.2678
40	5.3120	11.5936	11.6342	11.6734	11.0963	11.0256	11.0763
50	7.1649	16.6587	16.9275	16.9345	15.8355	15.8623	15.8623
60	9.3867	23.0339	23.0210	23.1056	21.5469	21.2532	21.3001

Load (kN)	Elastic energy (J)	Input energy (J)								
		Loading rates 1.0×10^{-2} mm/s			Loading rates 5.0×10^{-2} mm/s			Loading rates 1.0×10^{-1} mm/s		
		U11	U12	U13	U15	U16	U18	U19	U20	U21
10	0.5336	1.2306	1.2312	1.2403	1.2274	1.2523	1.2589	1.2116	1.2045	1.2112
20	1.7882	3.6150	3.6534	3.6589	3.6972	3.7067	3.6612	3.6537	3.5882	3.5534
30	3.3095	6.9999	7.0022	7.0145	6.8737	6.8188	6.8023	6.8322	6.7346	6.8422
40	5.3120	10.8820	10.8748	10.8220	10.7414	10.7387	10.7254	10.5063	10.3532	10.4333
50	7.1649	15.4601	15.4831	15.4923	15.0345	15.1073	15.0534	14.8308	14.8543	14.5567
60	9.3867	20.8840	20.7921	20.8812	20.3363	20.3645	20.3734	19.5584	19.4652	19.4753
70	11.4210	28.4815	28.5938	28.6645	26.8837	26.8534	26.8378	25.7337	25.3425	25.3325

TABLE 3: Linear energy storage fitting formula under the static-quasi-dynamic loading rate.

Loading rates (mm/s)	a	b	Fitting formula
1.0×10^{-3}	0.41019	0.20536	$U^e = 0.41019U + 0.20536$
5.0×10^{-3}	0.43912	0.12641	$U^e = 0.43912U + 0.12641$
1.0×10^{-2}	0.40720	0.46631	$U^e = 0.40720U + 0.46631$
5.0×10^{-2}	0.43143	0.3333	$U^e = 0.43143U + 0.33330$
1.0×10^{-1}	0.45195	0.24409	$U^e = 0.45195U + 0.24409$

5.2. Energy Evolution Analysis in Uniaxial Compression Test.

Figure 7 is the evolution curve of the total energy, elastic energy, and dissipated energy of sandstone under different loading rates. Figure 7(a) is the evolution curve of elastic energy and input energy. Deformation and failure of rock is the process of microcracks in its internal expansion, connection, penetration, and slip. The generation of new crack surfaces in rock needs to absorb energy, and the slip friction between the crack surfaces will dissipate energy [12]. The input energy and elastic energy of the rock both increase nonlinearly with the increase of loading. The total peak energy at loading rates of 1×10^{-3} , 5×10^{-3} , 1×10^{-2} , 5×10^{-2} , and 1×10^{-1} mm/s are 29.1199 J, 29.3998 J, 35.3227 J, 36.0304 J, and 36.7463 J. In the static-quasi-dynamic loading rate range, the peak energy of sandstone increases as the loading rate increases. In the static-quasi-dynamic loading rate range, the uniaxial compressive strength and stored elastic energy of sandstone increase with the increase of the loading rate, but when the load is equal, the stored elastic energy of the rock under different loading rates is equal. In the compaction stage, the load compacts the original microcracks in the rock; the dissipated energy consumed by the compaction of the cracks at different loading rates is little. Therefore, the deviation of the total energy-axial load curve from each other in the compaction stage is relatively small. The deformation in the elastic stage is mainly elastic. The higher the loading rate, the lower the friction of new cracks and original cracks in the rock

and the less the total energy absorbed under the same load. When the axial load of sandstone under different loading rates is equal, the smaller the loading rate, the lower the input energy-axial load curve. In the plastic stage, sandstone has more new cracks formation, propagation, and original crack propagation. The smaller the loading rate, the more sufficient the friction of the cracks inside the sandstone, and hence, the more energy is absorbed, which shows that the total energy-axial load curve of the rock further deviates.

Figure 7(b) shows the energy dissipation versus the axial load curve of sandstone under different loading rates. The dissipation energy grows nonlinearly with the increase of the load, and the dissipation energy of the rock is greatly affected by the loading rate. Since the sandstone used in this test has a similar internal structure, the dissipated energy generated during the internal crack closure process is relatively close. Therefore, under different loading rates, the dissipated energy-axial load curves in the compaction stage deviate to a small degree from each other. In the elastic stage of the rock, it is mainly elastic deformation and less crack formation. When the loading rate is low, the longer the bearing time of the specimen is, the small number of new cracks generated inside; it can sufficiently rub and develop, and the dissipated energy will be more; the small number of new cracks generated inside it can sufficiently rub and develop, and the dissipated energy will be more. Therefore, the degree of deviation between the rock dissipation energy-axial load curve at the elastic stage increases. In the plastic stage, there are a lot of original cracks and new cracks initiation and expansion. When the load is equal, the lower the loading rate, the internal cracks can fully friction, develop and connect, and generate more dissipating energy. Part of the work done by the external force on the rock mass is a conversion into the dissipated energy in the medium, which gradually loses the strength of the rock mass [23]. As a result, the lower the loading rate, the lower the strength of the specimen.

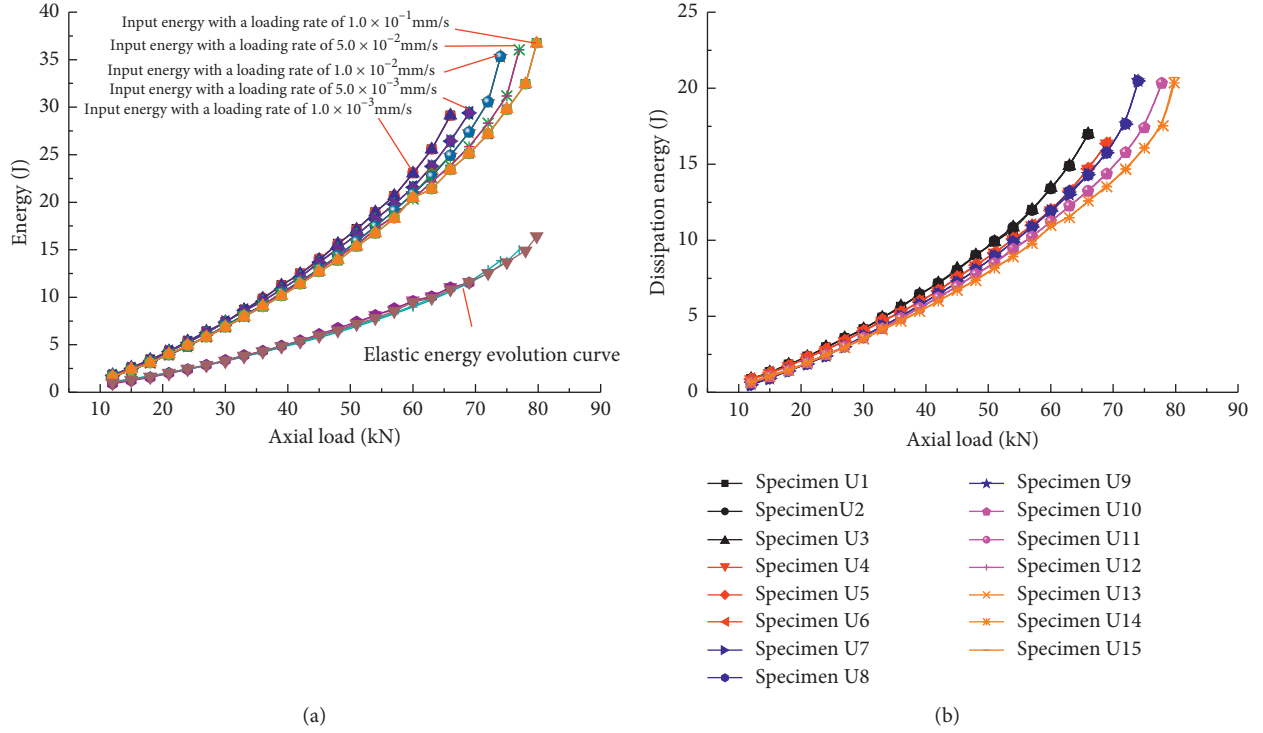


FIGURE 7: Evolution curve of sandstone under different loading rates. (a) Evolution curve of elastic energy and total energy. (b) Evolution curve of dissipated energy.

5.3. Comparative Analysis of Energy Evolution Analysis Methods. In the research on rock cyclic loading and unloading, it is a discovery that the load-deformation of rock unloading is affected by the hysteresis effect as a curve. The hysteretic effect of rock is due to the interfacial friction between the internal cracks and the viscosity of the internal liquid [13]. For example, Liu et al. [24] studied rock deformation parameters and damping parameters under cyclic loading, and Ge et al. [19] studied rock fatigue deformation characteristics under cyclic loading. In the previous energy evolution analysis in uniaxial compression tests, it is generally assumed that the unloaded stress-strain is a straight line, and the energy evolution during rock loading is analyzed based on the elastic modulus [12]. The calculation expression of the energy of uniaxial compression is [12]

$$\begin{aligned} u^e &= \frac{1}{2} \sigma_1 \varepsilon_1, \\ &= \frac{\sigma_1^2}{2E}, \end{aligned} \quad (3)$$

where u^e is the elastic energy density per unit volume, σ_1 is the axial stress, ε_1 is the axial strain, and E_1 is the elastic modulus of the rock unloading curve.

The energy evolution analysis method proposed in this paper is compared with the energy analysis method of the elastic energy density calculation formula. To facilitate the analysis, the energy unit is unified, and energy (J) is used for comparison. u^e represents the energy density per unit volume, so the conversion formula between the energy density and the energy of the specimen can be expressed as

$$\begin{aligned} U^e &= u^e V, \\ &= \frac{\sigma_1^2}{2E} V, \end{aligned} \quad (4)$$

where V represents the volume of the rock specimen.

The method of calculating elastic energy based on the elastic modulus is called Method 1. The energy analysis in this article is called the new method. According to the energy calculation formula, the key to calculating the rock energy by the formula method is the elastic modulus. The elastic modulus for loading rates of 1×10^{-3} , 5×10^{-3} , 1×10^{-2} , 5×10^{-2} , and 1×10^{-1} mm/s are 8.12 GPa, 8.23 GPa, 8.31 GPa, 8.61 GPa, and 8.8 GPa.

Figure 8(a) shows the elastic energy-axial load curves obtained by the two energy calculation methods. In the above research, compare the elasticity of the new method and the actual elastic. The two are almost coincident, and the difference is small and negligible. Therefore, the new method proposed in this paper is more accurate. The elastic energy under different loading rates calculated by Method 1 has differences when the loads are equal. And, there is a big difference between the elastic energy calculated by Method 1 and the elastic energy proposed by the new method. In summary, the elastic energy calculated by Method 1 is less accurate.

Figure 8(b) is a peak elastic energy of the sandstone obtained at different loading rates for two methods. On comparison of Method 1 and the new method, the maximum difference of peak elastic energy between the two is

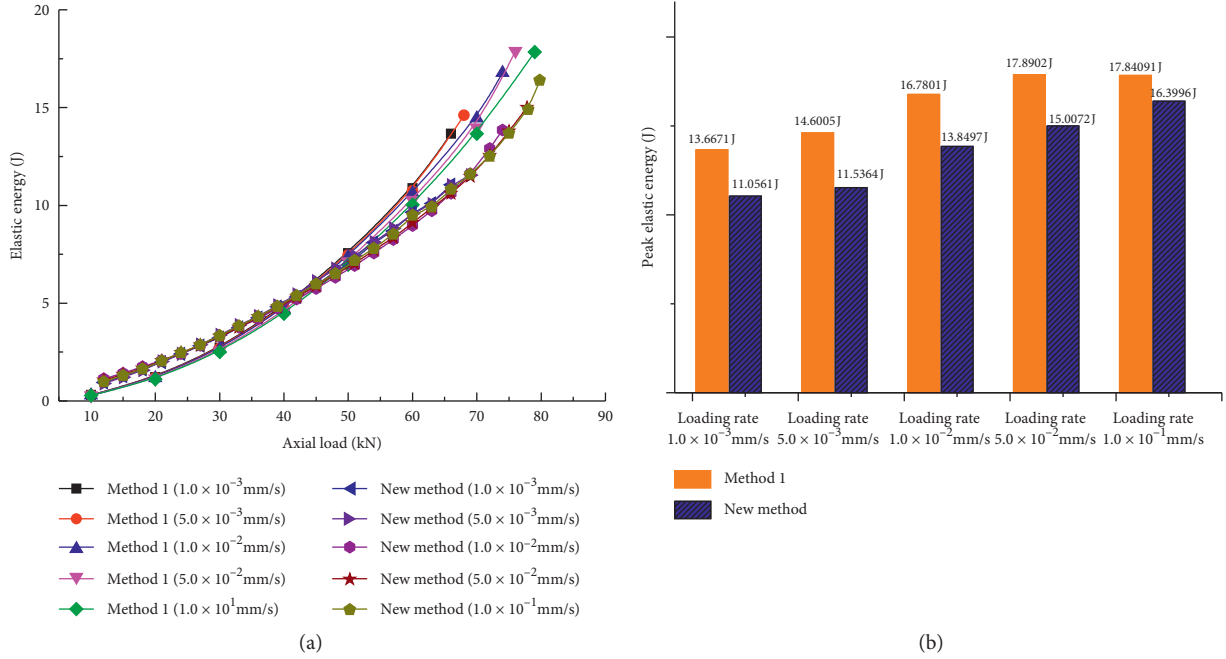


FIGURE 8: Comparison of calculated results of different elastic energy methods. (a) Elastic energy-axial load curve comparison. (b) Peak elastic energy comparison.

about 3.0641 J, which accounts for 26.56% of the energy value of the new method. Method 1 results are less accurate.

In summary, this paper proposes that the use of the uniaxial hierarchical loading and unloading test combined with the linear energy storage law can perform an energy analysis on the uniaxial compression test at any loading rate. The new method is highly accurate, which is the static-accurate load rate. The energy analysis of uniaxial compression tests provides new ideas.

6. Damage Analysis

Rocks can reflect the degree of damage to it during loading, and Chen et al. [25] proposed the energy dissipative rock damage variable D :

$$D = \frac{U^d}{U_p^d}, \quad (5)$$

where U^d represents the energy dissipation of rocks under any load and U_p^d indicates the energy dissipation during the peak load. $D = 0$ indicates that the rock is not damaged. $D = 1$ indicates complete rock destruction.

In the above studies, the rock energy complies with the linear energy storage law in the static-quasi-dynamic loading rate range, and the damage formula can be made based on the linear energy storage law:

$$D = \frac{U - (aU_p + b)}{U_p - (aU_p + b)}, \quad (6)$$

where U is the energy input to the entire load before the peak. The energy input U_p is input when the loading is peak.

a and b are the parameters fitted by the linear energy storage formula, and the parameters change irregularly when the loading rate changes.

Figure 9 is a damaged variable-axial load curve, and the rock damage variable increases as the load increases. Since the compaction stage is mainly to compact the microcracks inside the rock, the internal damage growth rate changes little. The damage variable in the compaction stage variation tendency is approximately linear with the load. In the elastic stage of the rock, elastic deformation is dominant. So the damage variable of rock also changes linearly with the load. In the plastic stage, there are more new cracks initiation and original crack propagation in the rock. Hence, the growth rate of the damage variable increases with the increase of the load. When the load near the peak, there is a mass of crack generation, propagation, penetration, and original crack propagation and penetration inside the rock. The damage inside the rock is increasing, and the specimen is damaged. The smaller the loading rate, the more the microcracks in the rock can have full friction and more energy dissipation. Therefore, when the load is equal, the smaller the rock loading rate, the greater the internal damage.

7. Discussion

In mining engineering, rock strength and failure criteria based on elastoplastic theory are usually the basis for judging engineering failure or failure [23]. However, the stress-strain curve has a certain degree of discreteness, which restricts the accuracy of the engineering design. Thermodynamics believes that energy conversion is the essential feature of the physical process, and the study of its energy features contributes to explore the nature of its destruction [15]. The elastic energy-

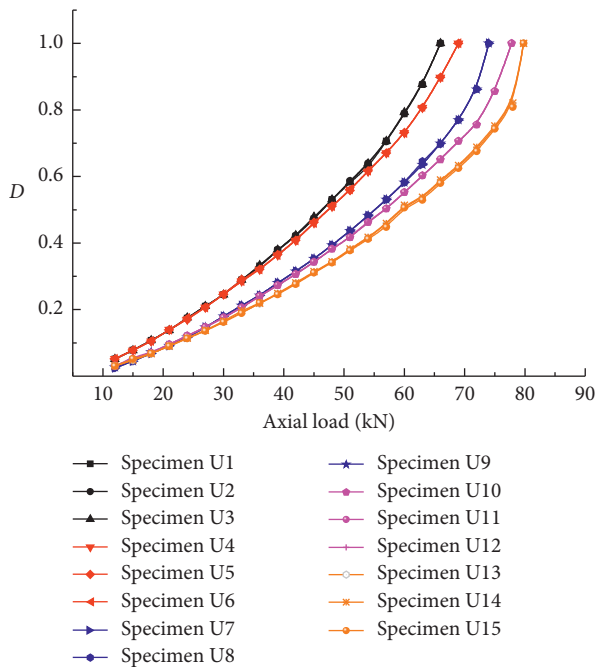


FIGURE 9: Damage variable-axial load curve.

axial load of the rock follows a specific curve. The energy storage limit of the elastic energy in the specimen is closely related to the loading rate. When the internal elastic energy is greater than the energy storage limit, the elastic energy is released, and the specimen is damaged. Determining the elastic energy-axial load curve of the material, combined with the material failure criterion of energy accumulation and release, is hopeful that the material failure can predict more accurately than the elastoplastic theory.

Energy analysis of the sandstone uniaxial compression test under different loading rates explored its energy evolution characteristics in the static-quasi-dynamic range. The dynamic failure of rock is the rapid release of internal elastic energy when the strength limit is reached [26]. In the research on the mechanical properties of rock under dynamic loading, it is the discovery that the mechanical properties of rock under dynamic loading rate are different from those in the static state [27]. Therefore, based on the study of the energy evolution law in the static and quasi-dynamic loading range, the law of energy evolution of rocks in the dynamic loading can be further studied, and the strength theory of dynamic loading based on energy evolution can be established. It stands a chance to reflect the nature of rock failure truer, and the research results have positive significance for topics such as rock failure energy mechanism and rock burst.

8. Conclusion

- (1) Under external load, stress concentration will occur at the original cracks inside the rock, resulting in large deformations and even local failures at the contact points. The debris formed at the stress concentration may fall off during unloading and fill

the nearby voids, which improves the friction characteristics and the rock bearing capacity.

- (2) The loading rate of rock is in the static-quasi-dynamic range, and its elastic energy by the loading rate and the number of cycles is less. The uniaxial grading loading-unloading tests can analyze the energy evolution at the same load in uniaxial compression. The analysis found that the energy evolution in the uniaxial compression test with different loading rates obeys the linear energy storage law.
- (3) The dissipated energy-axial load curves of sandstone with different loading rates gradually deviate from each other as the load increases. The higher the rock loading rates, the higher the input energy and elastic energy at the peak, but the low the input energy and elastic energy when the load is equal.
- (4) The energy of the uniaxial compression test of rock can be analyzed using the uniaxial incrementally loading -unloading test combined with the linear energy storage law. Compared with the energy evolution law obtained by the energy calculation formula, the new energy analysis method can analyze the energy evolution law more accurately and provides a new idea for the energy evolution law of rocks under different loading rates.
- (5) In the compaction stage and elastic stage of the rock, its damage variable-axial load increases approximately linearly. In the plastic stage, the growth rate of the damage variable increases with the loading. The internal damage of the rock increasing sharply at the loading is close to the peak load. When the loading is equal, the smaller the loading rate, the greater the internal damage of the rock [28].

Data Availability

The data used to support the findings of this study have not been made available because the experimental data involved in the paper are all obtained based on our designed experiments and need to be kept confidential; we are still using the data for further research.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This work was supported by National Natural Science Funds of China (Grant nos. 51974009, 51774012, 51674008, 52004005, and 52074006), Focus on Research and Development Projects in Anhui Province (201904a07020010), and Research Fund of Academic and Technical Leaders of Anhui Province (2018D187).

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