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Mechanical properties and energy dissipation of rock under acid corrosion and coupled static-dynamic loads

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The dynamic impact experiment were carried out to investigate the dynamic mechanical properties of different types of rocks under acidic environment and coupled static-dynamic loads. The experimental results showed that the mechanical properties of marble and red sandstone are affected by acid corrosion, impact pressure and coupled loading. Based on the principle of energy conservation and the experimental results, the energy dissipation law of the red sandstone under coupled static-dynamic loads was analyzed. The analysis results show that with the increasing of the impact pressure, the average strain rate increases, and the incident energy increases linearly, and the reflection energy and energy absorption show a slow growth trend; The transmission energy is almost unaffected by the impact pressure, and the fitting curve is approximate to a straight line. The results show that there is an obvious correlation between the dynamic strength of rock and the absorbed energy. The higher the impact pressure is, the greater the absorption energy is, the higher the strength of the rock under static and dynamic combination is.
Key words: rock mechanics; chemical corrosion; coupled static-dynamic loads; mechanical properties; energy dissipation

Исследовано влияние динамических и статических нагрузок на механические свойства различных типов пород в кислой среде. Экспериментальные результаты показали, что на механические свойства мрамора и красного песчаника влияют кислотная коррозия, ударное давление и статическая нагрузка. На основе принципа энергосбережения и результатов эксперимента проанализирован закон о рассеивании энергии красного песчаника при связанных статически-динамических нагрузках. Результаты анализа показывают, что при увеличении ударного давления средняя скорость деформации возрастает, энергия разрушения растет линейно, а энергия отражения и поглощение энергии проявляют медленный рост. Энергия передачи практически не зависит от ударного давления, а кривая фитинга приближается к прямой. Результаты показывают, что существует корреляция между динамической прочностью породы и поглощенной энергией. Чем выше ударное давление, тем больше энергия поглощения, тем выше прочность породы при статической и динамической комбинациях воздействия.

Механічні властивості і диссипация енергії гірської породи при кислотному впливі і пов'язаних статично-динамічних навантаженнях. *Liu Yong-sheng, Li Jin, Zou Jia-yu, Wu Qin-lan, Liu Wang*
Досліджено вплив динамічних і статичних навантажень на механічні властивості різних типів порід в кислому середовищі. Експериментальні результати показали, що на механічні

властивості мармуру і червоного пісковика впливають кислотна корозія, ударний тиск і статичне навантаження. На основі принципу енергозбереження та результатів експерименту проаналізовано закон про розсіювання енергії червоного пісковика при пов'язаних статично-динамічних навантаженнях. Результати аналізу показують, що при збільшенні ударного тиску середня швидкість деформації зростає, енергія руйнування зростає лінійно, а енергія відображення і поглинання енергії виявляють повільне зростання. Енергія передачі практично не залежить від ударного тиску, а крива фітинга наближається до прямої. Результати показують, що існує очевидна кореляція між динамічної міцністю породи і енергією поглинання. Чим вище ударний тиск, тим більше енергія поглинання, тим вище міцність породи при статичної та динамічної комбінаціях впливу.

1. Introduction

The deep rock is a kind of heterogeneous brittle media, the internal micro cracks are continuously developed and expanded under the influence of the deep complex environment and the high ground stress[1]. The rock mass with micro damage is subjected to dynamic loads due to excavation disturbance when the rock excavation under the condition of high stress. Therefore, the rock mass is subjected to complex dynamic and static loads, which results in the unstable development of rock crack and the failure. Guo L J et al. [2] studied the dynamic mechanical properties of granite under different impact pressures using the SHPB. The stress-strain relationship and failure process of rock under impact loading are discussed. It is found that the rock deformation process can be divided into four stages: initial compaction, stable deformation, nonlinear elasticity and failure. J.C.Li et al.[3] has performed dynamic mechanical tests of fractured rocks using the SHPB, and the propagation law of stress wave in fractured rock mass was discussed. The results showed that fracture width and water content have great influence on stress-strain relationship of fractured rock mass under dynamic action. According to the needs of deep rock mechanics, Li Xi-bing et al. [4-6] developed a static and dynamic loading test system for rock with medium and high strain rate, and the system is tested with different axial pressure, confining pressure and dynamic load. The results show that the dynamic strength of rock can be improved obviously by axial compression. The dynamic strength of rock increases with the increase of dynamic load, which shows the strain rate dependence under the combined action of static and dynamic loads. Zhao Fujun et al. [7] carried out the study of acoustic emission of rock under combined static and dynamic loading, the relationship between the acoustic emission energy, the load form and the crushing volume is analyzed. Yin tubing et al. [8] carried out the energy dissipation analysis of the rock under thermo-mechanical coupling. The results show that, at a given dynamic load, rock samples rock samples at temperatures of 20°C, 200°C and 300°C and axial pressure of 20 MPa have the maximal energy-absorb capability, but at temperature of 100°C rock samples under axial pressure of 0 MPa have the maximal energy-absorb capability.

With the development of deep underground engineering, many scholars[9-12] have carried out the research on the mechanical characteristics and energy dissipation of rock, and obtained a lot of meaningful research results. the influence of the deep underground complex environment on the rock properties can't be ignored. The acidity of deep groundwater plays an important role in the performance, failure mode, energy dissipation and so on. In this paper, we take into account the actual situation of deep underground engineering, acidified rock with acidic solution of pH=4. The impact test using static and dynamic system were conducted, and the energy dissipation law of the specimen are analyzed.

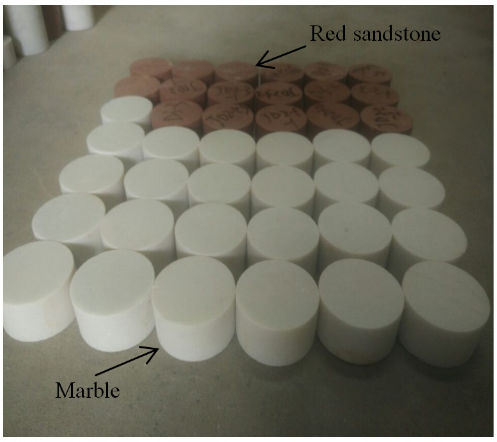

Fig. 1. Rock specimens

Table 1 The classification of loading mode

Test section	Impact pressure (MPa)					Axial static pressure (MPa)	Confining pressure (MPa)
Pure dynamic	0.45	0.50	0.55	—	—	—	—
One-dimensional	0.45	0.50	0.55	0.60	0.65	8	—
Three-dimensional	0.55	0.65	0.75	0.85	—	8	2

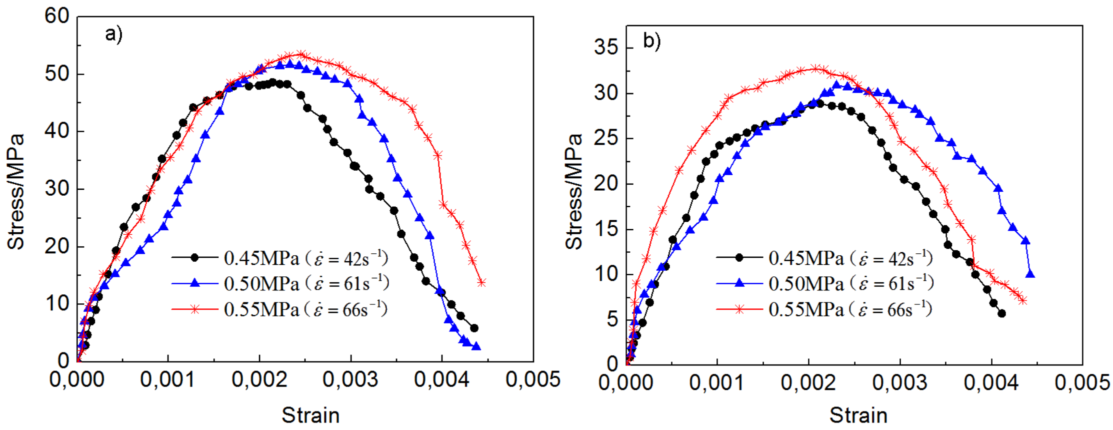

Fig. 2. The stress-strain curve under the action of pure dynamic loading. (a) red sandstone, (b) marble.

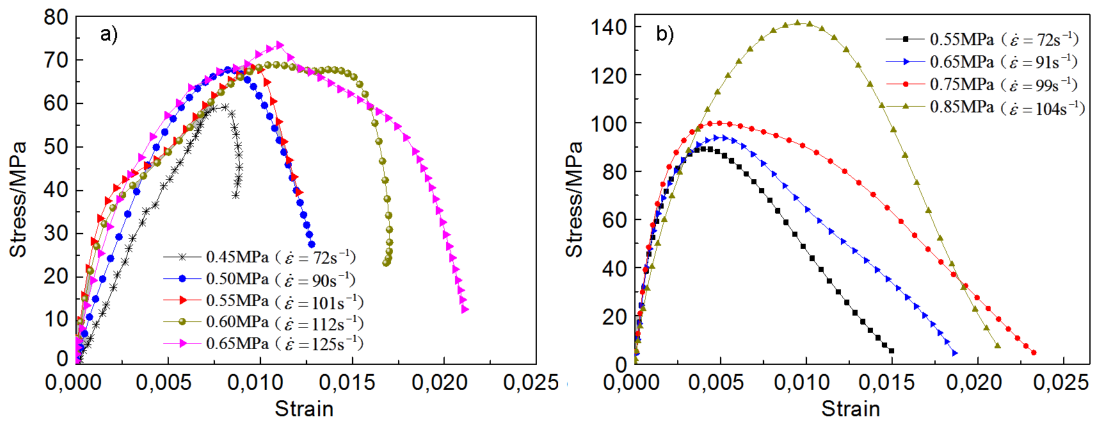

Fig. 3. The stress-strain curves of specimens under different conditions (a) one-dimensional loading, (b) three-dimensional loading.

2. Experiment

Red sandstone and marble are selected as the object of study. red sandstone is a sedimentary rock, and its compositions are quartz, calcite and so on. Marble belongs to metamorphic rock, mainly composed of calcite and dolomite. The sample of rock were taken in the same rock stratum, and the specimens are cylinders with a diameter of 50mm and a height of 25mm, shown as Figure 1.

In order to simulate the acidic environment of deep underground, the acid solution of pH=4 were prepared by the method of diluting hydrochloric acid, and then the specimen was immersed in the acid solution curing. The acidity of the solution was measured every 12 hours, and the pH value of acid solution was kept constant. The immersion time of the sample is 30 days.

The impact dynamic experiments are carried out by SHPB device and coupled static-dynamic loads device. The impact loads are pure impact loads, one-dimensional and three-dimensional coupled static-dynamic loads, the detailing loading schemes are shown as Table 1.

Table 2 The compression strength of specimens

strength (MPa)	Static	Pure dynamic Impact(MPa)			One-dimensional Impact (MPa)					Three-dimensional Impact (MPa)			
		0.45	0.50	0.55	0.45	0.50	0.55	0.60	0.65	0.55	0.65	0.75	0.85
Marble	19.1	28.9	30.9	32.8	-	-	-	-	-	-	-	-	-
Red sand-stone	31.0	48.6	51.7	53.5	59.1	67.9	68.5	69.0	73.4	89.2	93.8	99.9	141.3

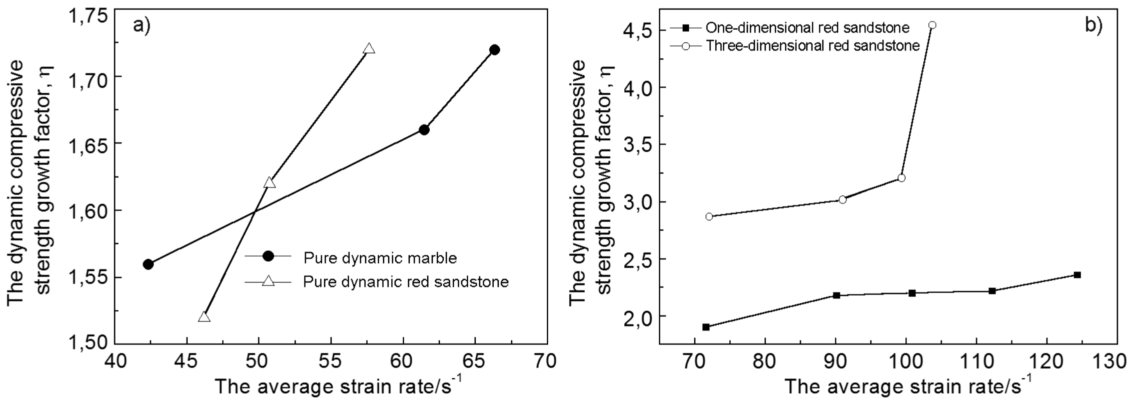

Fig. 4. Growth factor of dynamic strength, (a) pure dynamic, (b) coupled static-dynamic.

3. Results and analysis

The stress-strain curves of red sandstone and marble of the pure dynamic experiment is shown as Fig. 2, where $\dot{\varepsilon}$ is the average strain rate under different impact pressures.

From Fig. 4 we can found that the dynamic compression strength of red sandstone and marble increases with the impact pressure (average strain rate) increasing under pure dynamic loading. And the dynamic strength of the red sandstone is much larger than those of marble at close stain rate. The internal structure of red sandstone is more compact, acid corrosion has little effect on it, so after acid corrosion the dynamic mechanical properties of red sandstone reduce less. Due to the limitation of the experimental condition, the experiment of coupled static-dynamic loads carried out only for red sandstone, and the stress-strain curves of coupled static-dynamic loads are shown as Figure 3.

It can be found from Figure5. that the dynamic strength of red sandstone increases with the impact pressure increasing too under the one-dimensional and three-dimensional static-dynamic combined loading. The mechanical response of the acid red sandstone under one-dimensional loads and three-dimensional loads is similar, and all of process contain three main stages: the first stage is the elastic stage, the specimen is subjected to the instantaneous impact of the external load. At this point, the stress-strain curve of the rock shows a trend of upward growth. The cracks occur in specimen internal structure with the increasing of external impact time. Then specimen gradually enters the second stage, named the elastic-plastic stage. In this stage, the specimen began to damage by compression, but the stress is still rising till to the peak stress. The third stage is named plastic stage. At this stage the specimen loses its bearing capacity completely and the rock basically destroys. The stress-strain curve performs a rapid decrease from the peak stress point.

According to the stress-strain curves, the strength of the all specimens can be calculated shown in Table 2. In order to study the strength changing of the rock, the growth factor of strength is introduced in this paper, in which η is the ratio of rock dynamic strength to uni-axial compression strength $\eta=\sigma_d / \sigma_s$. The growth factor η of the specimens are shown in Figure 6. The growth factor η of all specimens increased with the average strain rate increasing, and the effect of red sandstone is more obvious than marble under pure dynamic loads seen from Figure 4 (a). The growth factor η of three-dimensional loads increase more obvious than one-dimensional loads with the strain rate rising form Figure 4 (b). Rock is a heterogeneous material, there are many original mi-

Table 3. Compression strength of rock samples

Rock specimen		Red sandstone		Marble	
		Normal curing	pH=4	Normal curing	pH=4
The uniaxial compressive strength (MPa)	First group	52.92	33.90	43.51	16.53
	Second group	60.64	28.67	36.25	19.85
	Third group	42.91	30.67	39.14	20.78
	Average value	52.16	31.08	39.63	19.05

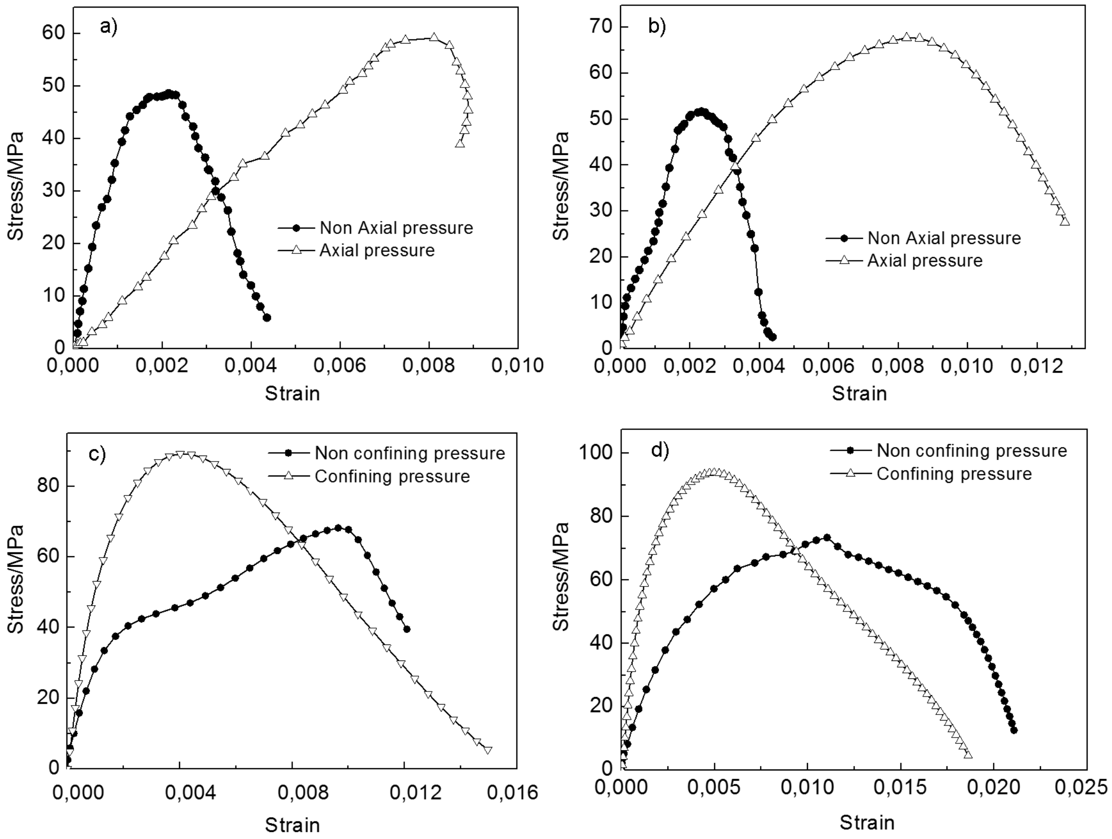

Fig. 5. Effect of axial pressure and confining pressure, (a) P= 0.45MPa, (b) P=0.50MPa, (c) P=0.55MPa, (d) P= 0.65MPa.

cro-crack inside the rock. At lower strain rate, the internal cracks of the rock have sufficient time to expand, so the specimen is easy to destroy, and the growth factor is not significantly. In high strain rate, the micro-cracks internal the rock is too late to expand, the bearing capacity improving. In contrast to one-dimensional loads and three-dimensional loads, the rock is subjected to three axis stress and has a great constraint effect under three-dimensional loads. The rock is not easy to crack under the dynamic impact load due to the great binding force, so the bearing capacity of the rock under three-dimensional loads improved more significantly.

In order to study the effect of acid environment on the mechanical properties of rock, the uniaxial compression experiment of the rock samples under acid and normal curing are carried out, and the results are shown in Table 3. The results showed that the uniaxial compression strength of rock samples decreased in different degrees after 30d immersion in pH=4 acid solution. After immersed in acid solution, the average value of compression strength of red sandstone is 31.08 MPa, and it is 41.25% lower than that of normal curing. The average value of compression strength of marble is 19.05 MPa, which is 51.9% lower than before. Form the test results, we know chemical corrosion has a great effect on the mechanical properties of the rock, especially to marble. So if there is a clear acidic environment in the underground project, we should do a good job on the performance of rock testing , and for security measures in advance.

Figure 5. (a), (b) are the stress-strain curves of the red sandstone under axial pressure and without axial pressure at the impact pressure of 0.45MPa and 0.5MPa . And the stress-strain curves of the red sandstone under confining pressure and without confining pressure at the impact pressure of 0.55MPa and 0.65MPa shown as Figure 5. (c) (d). From the Figure 5 we see the axial and confining pressure have significant influence on the dynamic compression strength of red sandstone. When the impact pressure is 0.45MPa and 0.50MPa, the peak stress of red sandstone under axial static load is 23.59% and 31.08% higher than that under non axial static load respectively. Thus, the axial static load greatly enhanced the peak stress of acid red sandstone. And it can be found that the peak strain of red sandstone under axial static loading is significantly higher than that under non axial static loading.

In the case of confining compression, the peak stress of the red sandstone under confining pressure is 30.79% and 27.87% higher than that of under non confining pressure when the impact pressure is 0.55MPa and 0.65MPa respectively. The confining pressure greatly enhanced the peak stress of acid red sandstone too. In deep underground environment, the dynamic compression strength of deep rock can be greatly improved because of the mutual compression of rock movement (confining pressure) caused by crustal movement.

4. Discussion

Based on the stress wave theory, the incident energy $W_I(t)$, the reflected energy $W_R(t)$ and transmitted energy $W_T(t)$ of split Hopkinson pressure bar (SHPB) can also be obtained as follows:

$$W_I(t) = \frac{A_e C_e}{E_e}\int_0^t \sigma_I^2(t)dt \qquad (1)$$

$$W_R(t) = \frac{A_e C_e}{E_e}\int_0^t \sigma_R^2(t)dt \qquad (2)$$

$$W_T(t) = \frac{A_e C_e}{E_e}\int_0^t \sigma_T^2(t)dt \qquad (3)$$

where A_e is the cross-sectional area of elastic rod; C_e is the elastic rod wave velocity; E_e is the elastic modulus of specimen; $\sigma_I(t)$, $\sigma_R(t)$ and $\sigma_T(t)$ are the incident, reflection and transmission stresses.

The energy of the specimen is $W_O = \int_0^{\varepsilon}\sigma(t)d\varepsilon(t)$ under the Uniaxial static load. For coupled static-dynamic loading, the axial pressure is added in SHPB system in advance. The absorbed energy W_S of the rock specimen under coupled static-dynamic loading can be calculated as formula (4):

$$W_S = W_I + W_O - (W_R + W_T) \qquad (4)$$

Absorbed energy W_S is mainly composed of three parts, of which the most important part is the fracture damage energy W_{FD}, its function is to formation fracture surface and crack, propagating and extending. The second part is the kinetic energy W_K of rock fragments. The third part is other forms energy, such as heat energy and radiant energy etc.. When the loading rate is not very large, the heat energy and radiation energy can be neglected. The research results indicated that the kinetic energy W_K of rock fragments is only about 5% of the absorbed energy W_S, while the fracture damage energy W_{FD} can reach to nearly 95% of the whole absorbed energy [13]. In this experiment, the specimens were corroded by acid solution, which led to the strength of the specimens lower, and there are few flying pieces after the specimens were damaged. So in the energy analysis, we used the absorption energy W_S to replace the fracture damage energy W_{FD} in this paper.

According to the formula (1) ~ (4), the energy of red sandstone under static-dynamic loading were calculated shown as Fig. 6, where A_e $=1.9625\times10^{-3}$m^2, C_e =5797m·s^{-1}, E_e =250GPa.

It can be seen from Figure 6 that the incident energy W_I of the acidified red sandstone increases with the average strain rate increasing, and them have a good linear relationship under one-dimensional and three-dimensional static and dynamic combination. The reflected energy W_R and the absorbed energy W_S show a slow increasing trend with the average strain rate increasing, and the growth trend is similar. The transmitted energy is hardly affected by the average strain rate, and it is stable between 15 ~ 23J.

Absorption energy is an important factor to control the strength and failure mode of the materials. The relation curves between the dynamic compression strength and the absorbed

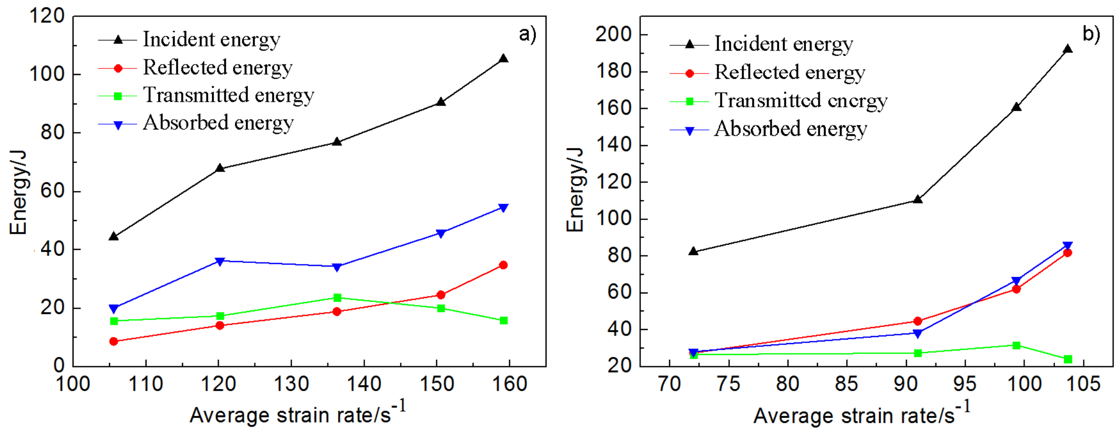

Fig. 6. The relationship between average strain rate and energy of acid red sandstone under the static and dynamic combination. (a) One-dimensional static and dynamic combination, (b)Three-dimensional static and dynamic combination.

energy of the experiment were given as shown in Figure 7. From Figure 8 we can see that the dynamic compression strength of the acidified red sandstone increases with the absorbed energy increasing whether in one-dimensional or three-dimensional state, and The strength increase linearly almost with the absorption energy increasing under one-dimensional loading. In the case of three-dimensional loading, when the absorption energy is lower than 70J the dynamic strength increase linearly, while the absorption energy is higher than 70J, the dynamic strength increases sharply. As we know the absorbed energy increases, and the energy transfer lags, the original crack failed to develop and expand in time, causing to deformation and failure delaying, so the dynamic strength improves. This effect will be more obvious under three-dimensional loading. Under the condition of three-dimensional loading, micro cracks are difficult to expand because of confining pressure.

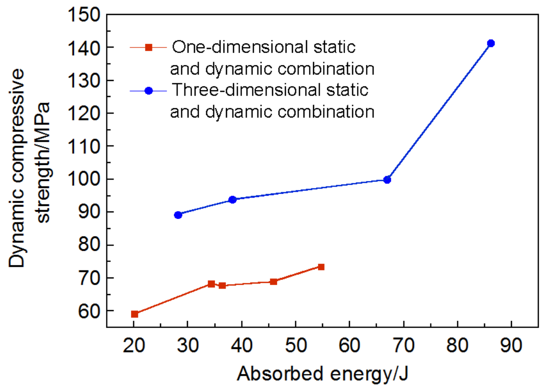

Fig. 7. The relationship between absorbed energy and dynamic compressive strength under the dynamic and static combination

5. Conclusions

In this paper, the dynamic experiment of rock under acid corrosion and coupled static-dynamic loads are carried out, and the energy dissipation law of the rock is analyzed. The results show that:

The dynamic compression strength of red sandstone and marble increases with the increasing of impact pressure (average strain rate) under pure dynamic and one-dimensional and three-dimensional dynamic loads. The growth factor η increase with the average strain rate rising, and the biggest η reach to 4.5 for three-dimensional coupled static-dynamic loads and 2.4 for one-dimensional. And axial pressure and confining pressure have great influence on the strength of rock.

Acid corrosion has a significant effect on the performance of the rock. The strength of marble lose 51.9% after 30 days acid immersing, and red sandstone losing 41.25%. So the underground project under chemical corrosion should pay special attention to safety.

The incident energy, the reflected energy and absorbed energy increases with the increasing of the impact pressure. The transmitted energy is almost unaffected by the impact pressure and the average strain rate, it is stable in the range of 15~23J.

The dynamic strength of acid rock has obvious correlation with the absorbed energy. The higher the impact pressure is, the greater the absorption energy is, the higher dynamic compression strength is. The increase of dynamic strength is mainly due to the micro cracks developing not timely, Especially for three-dimensional loading.

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