Research Article

The Effect of Confining Pressure and Water Content on Energy Evolution Characteristics of Sandstone under Stepwise Loading and Unloading

Shuren Wang,¹ Paul Hagan ,² Yanhai Zhao,¹ Xu Chang,¹ Ki-Il Song ,³ and Zhengsheng Zou¹

¹Opening Laboratory for Deep Mine Construction, Henan Polytechnic University, Jiaozuo, China

²School of Mining Engineering, University of New South Wales, Sydney, NSW 2052, Australia

³Department of Civil Engineering, Inha University, Incheon 22212, Republic of Korea

Correspondence should be addressed to Ki-Il Song; ksong@inha.ac.kr

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To investigate the mechanical properties and energy evolution characteristics of sandstone depending on the water contents and confining pressure, the uniaxial and triaxial tests were conducted. The test results show that the strain energy was stored in the sandstone samples at the prepeak stage, and that is suddenly released when the failure occurred, and energy dissipation is sharply increased at the postpeak stage. The damage and energy dissipation characteristics of the samples are observed clearly under the stepwise loading and unloading process. The critical strain energy and energy dissipation show a clear exponential relationship. The critical elastic energy decreases linearly as the water content increases. As the confining pressure increases, the critical elastic energy of the samples transforms from linear to exponential. The concept of energy enhancement factor is proposed to characterize the strengthening effect induced by the confining pressure on the energy storage capacity of the rock samples. The energy evolution of the sandstone samples is more sensitive to the confining pressure than that of the water content.

1. Introduction

In various underground engineering projects such as mining and tunnelling, stability is often governed by groundwater and disturbance during loading and unloading. The surrounding rocks show different responses during the process of loading and unloading, and the water content is also an important factor which can affect on the mechanical behavior of the rock. Therefore, it is significant to study the effect of water content and confining pressure on the damage process and energy evolution characteristics of the rock during stepwise loading and unloading process.

Aiming at the aforementioned problems, lots of experimental researches on the strength, deformation, and failure of different rocks have been carried out. For example, in order to explore the moisture effects on the mechanical properties of rock, Bagde and Petroš [1] conducted tests on dry and saturated samples under dynamic uniaxial cyclic

loading; they found that the dynamic fatigue strength and Young's modulus of the saturated samples all reduced obviously. Similarly, the mechanical characteristics of different rock specimens under cyclic loading were studied, and some valuable fruits were obtained [2–6]. For rock mechanics and rock engineering, it is essential to establish the water sensitivity of rock to the strength. It is necessary to assess the potential change of the strength and deformability of the rocks caused by moisture content. Experimental studies were carried out to explain the influence of water content on the strength and elasticity modulus under dry and water saturated conditions [7–13].

In fact, the deformation and failure of rock are forms of energy-driven instability. At present, the research on the energy evolution characteristics during the process of deformation and failure of rock is insufficient. Especially, the influences of the confining pressure on energy input, storage, and dissipation need further studies [14, 15]. In this paper,

uniaxial and triaxial compression tests were conducted with sandstone samples depending on the water contents and confining pressure to investigate the mechanical properties and energy evolution characteristics.

2. Materials and Methods

2.1. Sandstone Samples. The samples used for this study is Hawkesbury sandstones obtained from Gosford Quarry in Sydney, Australia. According to International Society for Rock Mechanics testing standards, the cylindrical specimens of 46 mm in diameter are drilled from the block sample and trimmed to be 100 mm in height. After drying and soaking treatment, tests were conducted for four different water content conditions (i.e., completely dry, 25, 50, and 100% water content).

2.2. Loading Equipment and Methods. The testing equipment is the MTS-815 rock test system provided by the School of Mining Engineering, University of New South Wales in Australia. The loading was controlled by the vertical force, and the loading rate was set to 0.05 kN/s. All samples were tested according to ISRM standards. The vertical force and the displacement in the process of testing were automatically recorded in real time by the data acquisition system. The compression tests were conducted under the confining pressures, such as 0, 2.5, 5.0, and 7.5 MPa.

For the stepwise loading test, the load was applied to the samples until it reached the level of 60% of the uniaxial compressive strength for the beginning. Then, the load is reduced to 10% of the uniaxial compressive strength. The maximum load for reloading is 12% higher than the previous load.

3. Results

3.1. Uniaxial and Triaxial Compression Tests. As listed in Table 1, the compressive strength of the sandstone samples decreases as the water content increases. And, the compressive strength increases as the confining pressure increases. The results show that the water content causes a significant attenuation effect on the compressive strength and deformation of the samples. The weakening is manifested when the water content of the samples changed from 0 to 25%: the average attenuation of the peak strength of the samples was 5.04 MPa, with an average decline of 11.79%. As shown in Figure 1, as the cycles of loading and unloading increases, the area of each hysteresis loop expands. The result is related to the constant accumulation of fatigue damage and plastic strain which implies energy dissipation becomes gradually significant. The similar observations are reported by Zuo et al. [16]. As the water content increases, the fatigue strength, strain, and slope of the curves decrease significantly, and the plastic loops transform from dense to sparse gradually. The increase of hysteresis loop area shows that the water content would aggravate the energy dissipation. As listed in Table 1, the peak strength and the residual strength increase as the confining pressure increases. When the confining pressure increases from 0 to 2.5 MPa, the average growth of the peak strength is 96.91%, and the lowest growth

TABLE 1: Compressive strength depending on the water content and confining pressure.

Confining pressure (MPa)	Water content (%)			
	0	25	50	100
0	26.32	21.04	16.67	13.96
2.5	41.89	39.23	37.71	30.13
5.0	54.01	48.99	45.46	40.21
7.5	62.84	55.64	52.10	47.69

of the peak strength is obtained from the saturated samples. As the confining pressure increases, the effect of confining pressure on the peak strength becomes indistinct.

3.2. Analysis of Stepwise Loading and Unloading. As shown in Figure 2, the loading curves show linear elastic characteristics and the unloading curves are approximately linear with slightly lower convex. After the first unloading, a relatively large residual strain can be observed between the unloading and loading curves. In the later process of unloading, the residual strain gradually increases, and its increment is almost same in each cycle.

The characteristics of the strain-stress curve can be observed: the plastic strain at the inflection point of the unloading stress is small. The bottom of the closed loop displays a vertical angle, the strain is kept invariable, and the stress rose steeply during the early stage of the reloading. As it is reported by Zuo et al. [16], it is supposed to be the elastic-lagged effect of the rock.

As it is mentioned earlier, a partial recovery of the deformation after a certain period is observed during the unloading process. From the viewpoint of energy, once the unloading behavior is being completed, a small part of elastic energy could not be released. This part of the residual energy would continue to be released and produce resistance, which led to a rapid increase in the elastic modulus when reloading at the next step.

As the cycles of loading and unloading increase, the area of each hysteresis loop expands. The result is related to the constant accumulation of fatigue damage and plastic strain which implies energy dissipation becomes gradually significant. The stress suddenly drops when it reaches the fatigue strength, and a lot of strain energy is released. As the water content increases, the fatigue strength, strain, and slope of the curves decrease significantly, and the plastic loops transform from dense to sparse gradually. The increase of each hysteresis loop area shows that the water content would aggravate the energy dissipation.

3.3. Energy Evolution Characteristics during Stepwise Loading and Unloading. The process of rock deformation and failure is accompanied by energy storage and consumption [17]. The external work can be treated as input energy U in rock, and the input energy can be translated into elastic energy U^e and dissipated energy U^d , the unit of three energy indexes is MJ/m³.

As shown in Figure 3, during the stepwise loading and unloading, the input energy U increases in the sandstone samples, and the elastic energy U^e and the dissipated energy

FIGURE 1: Stress-strain curves of the samples with different water contents. Uniaxial (a) and triaxial (b) compression tests under confining pressure 7.5 MPa.

FIGURE 2: Stress-strain curves of the samples with different water contents under loading and unloading conditions: (a) 0%, (b) 25%, (c) 50%, and (d) 100%.

FIGURE 3: Energy evolution curves of samples with different water contents: (a) 0%, (b) 25%, (c) 50%, and (d) 100%.

U^d also increase at the prepeak stage. Due to the microfracture damage and large plastic strain of the samples, the dissipated energy U^d is higher than the elastic energy U^e . When the stored elastic energy exceeds sandstone's capacity, the stored energy suddenly releases, and the elastic energy curve displays a radical drop, and there is a sharp rise in the energy dissipation curves when the samples failure occurred.

As the water content increases, three energy indexes U , U^d , and U^e of the samples vary significantly. The input energies of the sandstone are 0.208, 0.130, 0.089, and 0.067 MJ/m³ as the water content increases from 0, 25, 50, to 100%.

The water immersion plays a significant role on the energy input behavior. As shown in Figure 4, the critical input energy U_p and the dissipated energy U_p^d show a clear exponential relationship: as the water content increases, and the critical elastic energy U_p^e decreases linearly. The

attenuation of the critical energy can be clearly observed: the input energy of the samples decreased by 37% as the water content varies from 0 to 25%. As the sample approaches to saturation state, the weakening effect of water content on the energy limit becomes less remarkable.

3.4. Effect of Confining Pressure on Energy Evolution. As shown in Figure 5, the greater the confining pressure, the higher the critical elastic energy for the same water content condition. However, for the same confining pressure condition, the greater the water content, the lower the critical elastic energy. It can be found that the confining pressure can strengthen the storage capacity of the elastic energy. The partial elastic energy in the samples cannot be released due to the confining effect in the triaxial compressive strength

FIGURE 4: Characteristic curves of the critical energy. (a) U_p and U_p^e . (b) U_p and U_p^d .

FIGURE 5: Energy evolution curves with different water contents: (a) 0% and (b) 100%.

test. For example, the residual elastic energy of the dry samples increases to 0.0259, 0.0578, and 0.133 MJ/m³ as the confining pressures increases from 2.5, 5.0, to 7.5 MPa, respectively. The result demonstrates that the higher the applied confining pressure, the more the remaining residual elastic energy in the samples.

At the postpeak stage, the dissipated energy increases sharply due to the macroscopic crack occurrence, and the samples tend to be unstable. The critical dissipated energy increases as the confining pressure increases. The samples display larger plastic deformation under the higher confining pressure, and the dissipated energy is obviously different from that in the case of the uniaxial condition.

From Figure 6, linear upward trend of U_p^e and U_p can be observed. As the confining pressure increases, three critical energy indexes improve, but the extent of increment reduces gradually. However, as the water content increases, the

energy levels of the samples generally decrease. Three energy indexes of the saturated samples decrease obviously compared to those of the dry samples.

According to the relationship between the critical elastic energy U_p^e and the confining pressure C_f , the enhancement factor u_c of the energy storage limit can be defined to describe the strengthening effect of the confining pressure on the energy storage capacity of the samples as follows:

$$u_c = \frac{\Delta U_p^e}{\Delta C_f}. \quad (1)$$

When the confining pressure increases from 0 to 2.5 MPa, the enhancement factor u_c is higher than that of other pressure conditions. As the confining pressure continuously increases, u_c decreases gradually. When the confining pressure increases to a certain degree, it seems

FIGURE 6: Critical energy curves under different confining pressures: (a) U_p and (b) U_p^e .

there is no obvious effect of confining pressure on the energy storage limit. The average value of u_c is 0.026 and 0.019 in the dry and saturated samples, respectively. u_c of the saturated samples reduces by 26.9% on average compared to that in the dry state. It can be found that u_c decreases as the water content increases.

Based on the test data, the fitting function of the energy storage limit of the sandstone is obtained as follows under coupling action of the confining pressure and the water content:

$$U_p^e = 0.0111C_f - 0.0644m_c + 0.0877. \quad (2)$$

In order to compare the influences of the confining pressure and the water content on the energy evolution of the sandstone samples, the limit value of the energy input and storage is used as investigation index Y . The limit value of confining pressure and the water content is used as the influencing factor X . The sensitivity analysis is performed by using the sensitivity formula as follows:

$$S = \frac{\Delta X/X}{\Delta Y/Y}. \quad (3)$$

The critical energy index is used as the reference when the confining pressure is 5.0 MPa and the water content is 50%. The value $\sum|S|$ of the confining pressure C_f is 1.36~1.59, and that value of the water content is less than 1.10. Compared to the water content, the influence of the confining pressure on the input, storage, and dissipation behavior of the energy is more significant.

4. Discussion

Based on the test results, it is found that mechanical properties and the energy characteristics of sandstone are governed by the confining pressure and water content. Therefore, it is more practical to study the energy input,

FIGURE 7: Characteristic curves of critical elastic energy with different water contents.

storage, and dissipation considering the influence of the confining pressure, the water content, and the external loading modes.

The internal damage in the samples can be clearly observed under the stepwise loading and unloading process; the energy dissipation of the damaged samples is obvious, and its energy storage capacity becomes poor. During the uniaxial and triaxial compressive strength tests, the elastic energy is accumulated as long as the stress is smaller than the peak stress. The elastic energy would be stored before the local damage occurred. When the elastic energy exceeds its capacity, sudden failure accompanies a radical release of energy. Sometimes the stored elastic energy would not be completely released. The energy evolution of the samples can

be described with the input energy U , the elastic energy U^e , and the dissipated energy U^d . Each energy index has a peak value. When the elastic energy exceeds its limit of capacity, it would suddenly release which causes the rock failure. After the rock completely lost the bearing capacity, the input energy and the dissipated energy reach the maximum values. The confining pressure directly affects the overall level and the growth rate of the energy in rock.

The input energy, elastic energy, and dissipated energy increase significantly in the prepeak stage. The growth is accelerated as the confining pressure increases [15]. Although the confining pressure increases to a certain extent, the capacity of the energy storage cannot be improved. In the uniaxial compression strength test, the elastic energy curve drops sharply and the stored energy is completely released within a short time in the postpeak stage. In the triaxial compressive strength test, the confining pressure shows the hindering effect on the release of the elastic energy: the higher the confining pressure, the more the remaining residual elastic energy.

Under the stepwise loading and unloading conditions, the unloading action also induced energy release, but it was different from the energy release in the postpeak stage under uniaxial and triaxial compressive conditions. The released energy caused by unloading action was relatively smaller and would not cause the rock failure, while the elastic energy was stored again in the next loading step. The multistep loading and unloading caused microdamage of the rock samples, and the dissipated energy under stepwise loading and unloading was greater than that under the compressive loading condition. So, the effect of loading mode on energy evolution could be revealed in the three types of experiments.

Compared with the dry samples under the same loading conditions [18], the calculation results of the energy indexes of the partially and fully saturated sandstone samples are relatively lower. The results demonstrate that the effect of water content could not be ignored in the energy evolution of the rock. Moreover, the effect of confining pressure is more obvious than that of the water content. The relationship between the water content and the capacity of rock energy storage is obtained by calculation as shown in Figure 7. The critical elastic energy of the samples decreases linearly when the confining pressure is low, and it decreases exponentially when the confining pressure is high. The critical elastic energy decreases as the water content increases. It can be concluded that the energy release from the wet rock is relatively lower than that from the dry rock under the same stress environment. The water injection can be considered to reduce the stored energy in deep or hard rock engineering with high stress.

5. Conclusions

To investigate the mechanical properties and energy evolution characteristics of sandstone depending on the water contents and confining pressure, the uniaxial and triaxial tests were conducted. From the series of test, salient findings are listed below.

As the water content increases, the compressive strength and elastic modulus of the sandstone samples decrease, but

the compressive strength of the sandstone samples increases as the confining pressure increases.

During the stepwise loading and unloading process, the elastic energy curve is lower than that of the dissipated energy; the energy behavior of the samples mainly displays dissipation. The damage and plastic deformation also govern the energy storage capacity of the samples.

As the confining pressure increases, it significantly enhances the input energy, the elastic energy, and the dissipated energy of the samples in the triaxial compressive strength test. However, the water content weakens the input, storage, and growth rate of the strain energy, and it would aggravate the energy dissipation.

The critical indexes of the energy input and storage decrease as the water content increases. The fitting function of the storage limit of the elastic energy is obtained depending on the confining pressure and the water content. However, the effect of the confining pressure on the energy input, storage, and dissipation of the samples is more significant than that of the water content.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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