Experimental study of the effects of moisture content on the mechanical properties of sandstone under uniaxial compression

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Abstract: Water inside the micropores has a tremendous influence on the mechanical properties and damage patterns of rocks. To investigate the effects of different moisture contents on the cracking behavior of sandstone under different compression conditions, four groups of sandstone samples with moisture contents of 1.00\%, 2.50\%, 3.50\% and 4.50\% were used for uniaxial compression and cyclic loading-unloading experiments. The results show that the compressive strength and elastic modulus decrease with the increase of moisture content. The ultimate failure patterns for samples are all shear failure modes with different dip angles. In the unloading experiments, the dissipated energy and residual strain decreases with the increase of moisture content during the unloading stage with low stress and increases obviously during the unloading stage with high stress.

1 Introduction

Damage involved in rock engineering has brought in many problems including dam damage, landslides and tunnel collapses, resulting in huge economic losses and human casualties. There are many factors that affect the failure behavior of rock, such as the confining pressure, temperature, porosity, cyclic loading, historical stress\textsuperscript{[1-4]}. Among theses various factors, water plays an important role\textsuperscript{[3-6]} in the rock properties, especially in the strength. For example, Kim\textsuperscript{[7]} investigated the effects of moisture content and loading rate on the mechanical properties of geomaterials, and the results showed that the static and dynamic strengths of dry specimens were higher than those of saturated specimens. Although lots of previous works have studied the effect of moisture content on rock properties in detail, there still are some shortcomings.

One is that most of the previous works have only considered two states of dryness and saturation, and there are rare reports to study the effects of different moisture contents on the fracturing behavior and mechanical properties.

The other one is that the moisture content has not only an effect on the mechanical properties of the rock during the compression, but also on the unstable propagation of macrocracks. However, its mechanism is still not well-understood.

To deeply addressed the above shortcomings, four groups of sandstone samples with different moisture contents were used for uniaxial compression and cyclic loading-unloading experiments to...
study the effect of moisture contents on the mechanical properties of the rocks during different stages of compression.

2 Materials and Methods
The samples were made of white sandstone collected from Fujian mine, which has a maximal moisture content of 4.5% and a density of 196.25 g/cm³ in its natural state. Four groups of samples with the moisture contents (ω) of 1%, 2.5%, 3.5% and 4.5% were configured, respectively. Three parallel experiments were taken account for each group to reduce the experimental errors.

2.1 Mechanical experiments
The standard cylindrical specimens of Φ50 mm×100 mm were grouped and numbered according to four different moisture contents: ω=1.00%, ω=2.50%, ω=3.50%, and ω=4.50%, and then are compressed by uniaxial compression and loading-unloading. According to the stress-strain curves obtained from uniaxial compression of samples with different moisture contents, their compression process is divided into four stages: microflaws compaction and closure stage, elastic deformation stage, stable crack propagation stage, unstable crack growth and irrecoverable deformation stage. According to the uniaxial stress of each stage of specimen, the cyclic loading-unloading experiments were carried out for several repeated loading and unloading cycles on specimens with different moisture contents, and the maximal load applied at each time was greater than the maximal load of the previous cycle. The increment of unloading stress is set to 5MPa.

![Fig. 1. Fracture image of specimens with different moisture contents](image)

Fig. 1 shows the ultimate failure patterns for samples with different water content. From the figure, it can be seen that the all samples have complex types of cracks. Including oblique shear cracks, X-shaped cracks, and tensile cracks parallel to the loading direction, etc. By comparing the cracks in parallel groups of specimens with different moisture contents, it was found that the X-shaped shear cracks were more like to generate when the moisture content is high.
Fig. 2. Stress-strain curves of specimens with different moisture content

The stress-strain curves with different moisture contents after uniaxial compression are shown in Fig. 2. From the curves, it can be found that the peak stress and strain at the peak point both decrease with increasing moisture content.

Fig. 3 shows the stress-strain curves of the specimens with different moisture contents for the cyclic loading and unloading experiments. It can be seen from Fig. 3 that the peak strength does not always occur in the last cycle.
By analyzing Fig. 2 and Fig. 3, it is easy to find that the maximal compressive strength in cyclic loading and unloading experiments is slightly less than that of uniaxial compression. This difference increases with increasing moisture content.

3 Results & Discussion

Fig. 4. Relationship between the moisture content and modulus of elasticity, and peak stress
Fig. 4 shows the relation between the moisture content and modulus of elasticity, and between the moisture content and compressive strength. The strength of saturated specimens decreased by 32.2% compared to that of dry specimens. The modulus of elasticity gradually decreases with the increase of moisture content, but the decrease of elasticity modulus tends to be more linear than the decrease of compressive strength.

3.1 Energy change mechanism
By extracting each hysteresis loop curve formed after each loading-unloading cycle in Fig. 3, the energy changes in each compression stage will be analyzed in detail.

Fig. 5 shows the relation between the dissipated energy and the moisture content. At the unloading stress of 5 MPa and 10 MPa, the dissipated energy slightly decreases with the increase of moisture content, as shown by the black and red curves in Fig. 5, which is caused by that pores and microcracks containing water closure more slowly than those without water during the process of microflaws compaction and closure stage. When the unloading stress rises to 20 MPa, as shown by the green curve in Fig. 5, the cracks grow unstable and irrecoverable deformation stage occurs. More irrecoverable deformations occur in the specimens with high moisture content at this stage than those with low moisture content. Thus, the dissipated energy increases with the increase of moisture content at the unloading stress of 20MPa.

3.2 Residual strain change mechanism
Fig. 6 shows the residual strain after unloading at different compression stages extracted from Fig. 3.
From Fig. 6, it can be seen that the four curves representing different water content all have a trend of decreasing first and then increasing. At the unloading stress of 5 MPa, at this stage the initial fissures in sandstone samples are compressed and closed under axial stress. For samples with high moisture content, the residual strain generated in this stage is lower than that for samples with low moisture content. When the unloading stress increases from 5 MPa to 10 MPa, the residual strain produced in the elastic deformation stage is less than that in the previous stage. As the successive increase of axial stress and microcracks coalesce, macrocracks form and propagate in a stable way, the residual strain starts to increase. When the stress further increases to 20MPa and unstable crack growth and irrecoverable deformation stage occur. At the stage, increase in plastic deformation leads to an increase in residual strain.

4 conclusions

This paper detailedly studies the effect of different moisture contents on the mechanical properties during different compression stages for uniaxial compression and cyclic loading-unloading experiment. The primary conclusions are drawn as follows:

(1) Compression strength and elastic modulus decrease with the increase of moisture content. The decrease of elasticity modulus is more linear than the decrease of compressive strength. The ultimate failure patterns of rocks with different moisture content are complex, but the X-shaped shear cracks were more likely to generate when the moisture content is high.

(2) The dissipated energy decreases slightly with the increase of moisture content during the unloading stage with low stress. For unloading stage with high stresses, the dissipated energy of the specimen increases obviously with the increase of moisture content.

(3) When the unloading stress is at 5MPa and 10MPa, the residual strain shows a decreasing trend with the increase of moisture content. After the unloading stress exceeded over 20 MPa, the unstable crack growth and irrecoverable deformations stage occur in the samples. The residual strain increased obviously with the increase of moisture content.

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