Analysis of damage characteristics of fine and medium-fine cracked sandstones under a complex stress path

Huarui Hu1,2 | Binwei Xia1,2 | Yang Li1,2 | Yafei Luo1,2 | Jiajun Peng1,2

1State Key Laboratory of Coal Mine Disaster Dynamics and Control, Chongqing University, Chongqing, China
2School of Resources and Safety Engineering, Chongqing University, Chongqing, China

Correspondence
Binwei Xia, State Key Laboratory of Coal Mine Disaster Dynamics and Control, Chongqing University, 400044 Chongqing, China.
Email: xbwei33@cqu.edu.cn

Yafei Luo, School of Resources and Safety Engineering, Chongqing University, 400044 Chongqing, China.
Email: luoyafei@cqu.edu.cn

Funding information
Major Special Projects of Science and Technology in Shanxi Province, Grant/Award Number: 20191101015; National Natural Science Foundation of China, Grant/Award Number: 51974042

Abstract
In underground engineering such as mining and tunnel excavation, the rock mass is often subjected to repeated loading and unloading stress environments. Herein, true triaxial cyclic loading and unloading tests are carried out on fine sandstone and medium-fine sandstone specimens with cracks of different angles. The test results show that the mechanical properties of fine sandstone and medium-fine sandstone samples show obvious differences, and the crack angle has a significant effect on the mechanical properties of the sandstone specimen. During the experimentation, the expansion phenomenon of medium-fine sandstone is more obvious than that of fine sandstone, and its brittleness is also weaker. The damage law of the sample has nothing to do with the type of sandstone. The damage caused by the stress in the \( \sigma_1 \) direction varies linearly with the cumulative damage of the specimen, however, the damage caused by the directions of \( \sigma_2 \) and \( \sigma_3 \) grow nonlinearly in terms of the cumulative damage of the specimen. The hysteretic loop dissipated energy of the same type of sandstone specimens at different angles are dissimilar, and the dissipated energy increases with the increase of the crack angle. Based on the equivalent irreversible strain and the hysteretic loop dissipated energy, the damage law of the rock strength is analyzed. The obtained results reveal that the index based on the equivalent irreversible strain is helpful in exploring the damage degree of rock in the initial stage of cyclic loading and unloading. Furthermore, the damage index established based on the energy dissipation concept is beneficial to predicting the damage and failure law of rock in the advanced stage of loading.

KEYWORDS
cracked sandstone, damage characteristics, energy dissipation, irreversible strain, true triaxial cyclic loading and unloading
1 | INTRODUCTION

During the excavation process of tunneling, mining engineering, and deep-geological engineering, the rock mass is usually subjected to cyclic loads, and it causes periodic disturbances to the surrounding rock by cyclic loading and unloading, which affects the engineering stability. In the process of cyclic loading and unloading, the failure and instability of the rock mass do not occur suddenly, but in the process of gradual failure. Additionally, sandstone, as a sedimentary rock broadly distributed on the surface, is extremely common in underground engineering. Affected by the geological structures, sandstones of various textures exist in the same area, such as fine sandstone and medium-fine sandstone. Due to the existence of natural cracks and other defects in the rock mass, the deformation and damage process of the rock mass is usually complicated. From the engineering stability standpoint, it is of great importance to examine the damage and failure laws of fine sandstone and medium-fine sandstone with different textures under the action of cyclic load disturbance accounting for the nonlinear deformation and crack characteristics.

To date, a large number of scholars have conducted in-depth research on the mechanical properties of rocks under uniaxial cyclic loading and unloading and triaxial conditions. Li et al. studied the damage law of granite and marble under uniaxial cyclic loading and unloading by using acoustic emission, and the acoustic emission characteristics and fractal characteristics of the specimens in different test stages are analyzed, so the rock failure law is predicted based on this. Chen et al. studied the failure laws of sandstone, limestone, and concrete specimens under cyclic loading and unloading, and different material specimens showed different strengthening effects and failure laws. Voznesenskii et al. studied the mechanical properties of limestone, gabbro, and marble under cyclic loading and unloading, and the damage and failure laws of the three types of rock were significantly different. Peng et al. studied the failure characteristics of sandstone specimens with different crack angles under cyclic loading and unloading conditions. Xia established the clump parallel-bond model (CPBM) and analyzed the failure process of cracked rocks with different dip angles under cyclic loading and unloading. Wang et al. studied the damage law of marble ring damage under cyclic loading and unloading and showed that the damage caused by cyclic loading and unloading to the specimen has a significant impact on the failure mode of the specimen. Meng et al. studied the characteristics of acoustic emission during rock deformation under cyclic loading and analyzed the damage degree of rock combined with the Kaiser and Felicity effects of rock. Liang et al. studied the mechanical properties of rock under triaxial cyclic loading and unloading and focused on the failure mode of rock under cyclic loading and unloading. Xiao et al. studied the failure characteristics of rock under true triaxial cyclic loading and unloading, focusing on the influence of cyclic loading and unloading times on rock mechanical properties. In addition, a large number of scholars have studied the mechanical behavior of cracked rock under cyclic loading and unloading, but most of them only analyzed the damage and failure results of the rock, which has a certain reference for understanding and predicting the overall strength of the rock. However, in practical engineering applications, the stress environment of rocks is complex, and it is more conducive to solving complex engineering problems with the help of a true triaxial test system to study rock mechanics problems.

On the other hand, under the same disturbance stress environment, the failure degree and failure mechanism of various types of rocks are considerably different, and the above literature survey confirms this issue. Particularly for the rock mass which is commonly composed of multilayered rock layers. In practical engineering, the failure and instability of various layers of the rock have different effects on the project. The Tashan Mining Area, Datong City, Shanxi Province, China has a typical multilayered rock mass structure. The overburden hard roof is composed of fine sandstone and medium-fine sandstone, and the mechanical properties of the consisting fine sandstone and medium-fine sandstone are expressively dissimilar. Therefore, it is of great importance for the construction of similar projects to examine the mechanical characteristics of fine sandstone and medium-fine sandstone under the action of cyclic loading and unloading.

Based on the discussion provided above, this study focuses on the progressive failure process of fine and medium-fine sandstones subjected to complex stress paths. The main purpose of the present study is to examine the damage evolution law for fine and medium-fine sandstones with various crack angles. Based on the irreversible strain and dissipated energy, a rock damage evaluation index is proposed to analyze the failure process of sandstones. It is aimed to provide a crucially solid basis for the design and construction of geotechnical structures.
2 | MATERIALS AND METHODS

The rocks are taken from the fine and medium-fine sandstone layers in the Datong mining area of Shanxi Province, China, and the rock is cut into a 50 × 50 × 100 mm specimen. The mesostructures of the two types of sandstone are shown in Figure 1A,B. After the grinding procedure, the specimens are prefabricated with four specified angles of cracks, namely, 0°, 30°, 60°, and 90° by a high-pressure water jet machining system (Figure 1C). First, set the fracture parameters (length, width, angle, and position) in the control system. Then, place the sample on the operating table and adjust the water jet outlet to be directly above the center of the specimen. Finally, start the control system, and the water jet outlet automatically moves according to the set parameters to complete the cutting. The length of the crack is 15 mm and the width is 1 mm. The physical parameters of sandstone are shown in Table 1.

The test equipment is the Geotechnical consulting and Testing Systems (GCTS) triaxial rock test system (RTX3000), whose schematic representation has been demonstrated in Figure 2. The circular pressure chamber is pressurized by confining pressure regulation system by employing the control and data acquisition system. The maximum values of the axial load and the transverse stress in order are 2500 kN and 70 MPa. The axial stress is applied by a rigid loading frame, while the lateral stresses are exerted by the loading board on both sides. During the experimentation, the axial and lateral deformations of the understudy specimens are appropriately collected by sensors with measurement error lower than 0.25%, and the measurement range is from −6 to 6 mm.

The stress loading method has been demonstrated in Figure 3, where \( \beta \) denotes the inclination angle of the prefabricated crack in the specimen. To proceed with the test, the stress is initially applied to a predetermined value at the rate of 2 MPa/min (\( \sigma_1 = 11.44 \text{ MPa}, \sigma_2 = 12.9 \text{ MPa}, \sigma_3 = 7.24 \text{ MPa} \)). Subsequently, the cyclic loading and unloading are carried out at a speed of 0.04 mm/min in the direction associated with \( \sigma_1 \). During loading, the postcycle stage is about 20 MPa higher than the loading peak value of the previous cycle. During unloading, the specimen is unloaded to a fixed value (see Figure 3B).

3 | RESULTS

3.1 | Characteristics of the stress–strain curves for fine and medium-fine cracked sandstone specimens

The test results demonstrate that the strength of both fine sandstone and medium-fine sandstone varies with the crack angle, and the compressive strength of
sandstone specimens increases gradually with the increase of crack angle. The peak strengths of the fine sandstone specimens at 0°, 30°, 60°, and 90° are 97.01, 101.07, 105.96, and 121.88 MPa, respectively. The peak strengths of these medium-fine sandstone specimens in order are 84.30, 87.07, 100.59, and 108.44 MPa. The obtained results show that the sandstone particle size has a substantial effect on its strength. In Figures 4A and 5A, the typical stress–strain curves of fine and medium-fine sandstone specimens have been presented for the case of a crack angle of 30°, respectively. For fine sandstone,

| Sandstones          | Natural water content | Density (kg/m³) | Porosity (%) | Poisson’s ratio |
|---------------------|-----------------------|----------------|--------------|----------------|
| Fine sandstone      | 3.89                  | 2530           | 5.7          | 0.16           |
| Medium-fine sandstone | 5.16                | 2436           | 10.2         | 0.18           |

**Table 1** Physical parameters of two types of sandstone

![Schematic representation of the Geotechnical consulting and Testing System](image)

**Figure 2** Schematic representation of the Geotechnical consulting and Testing System (A) Test schematic (B) Test system diagram.
when the stress increases to the elastic limit, plastic deformation of the specimen occurs, the stress–strain curve deflects considerably, and the $\varepsilon_1-\sigma_1$ curve is stepped. However, the medium-fine sandstone specimens do not exhibit the characteristics displayed above. Furthermore, when the specimen is suddenly broken, the stress–strain curve of the fine sandstone specimen suddenly drops, while the medium-fine sandstone specimen drops slowly, indicating that the fine sandstone is more brittle than the medium-fine sandstone. During the cyclic loading and unloading process, the stress unloading curve is not coincident with the loading curve, resulting in a hysteretic loop (see Figure 4B–D). The number of hysteresis loops formed by various specimens during the test is different, indicating a difference in the number of loading and unloading cycles experienced by the specimens before failure. Furthermore, the area of the hysteresis loop formed during the latter loading and unloading cycle is larger than that of the present one.

As shown in Figures 4A and 5A, the values of $\varepsilon_1$, $\varepsilon_2$, and $\varepsilon_3$ gradually grow during the loading process of fine sandstone and medium-fine sandstone specimens. The plot of $\varepsilon_1$ moves up and down periodically with loading and unloading, forming a hysteresis loop (see Figure 4B–D). The values of $\varepsilon_2$ and $\varepsilon_3$ are much smaller, the expansion phenomenon is not obvious, and there is no apparent hysteresis loop. Furthermore, during the cyclic loading and unloading test of the fine sandstone specimen, $\varepsilon_1$ is always positive. Its sign suddenly changes to negative when the specimen is broken, and the specimen expands significantly at this time. For medium-fine sandstone, $\varepsilon_3$ is always negative, the expansion of the specimen is obvious, and it suddenly decreases when the specimen is broken.

3.2 Characteristics of the failure patterns for sandstone specimens with different crack angles

As shown in Figures 6 and 7, the fine sandstone and medium-fine sandstone specimens with various crack angles mainly suffer from shear failure. The shear fracture surface of the specimen has been shown in Figures 6 and 7. With the increase of the prefabricated crack angle, the angle between the fracture surface of the specimen and the plane of the prefabricated fracture becomes larger and larger. The ranges of such an angle for the fine sandstone and medium-fine sandstone specimens are $66^\circ-160^\circ$ and $71^\circ-152^\circ$, respectively. With the growth of the crack angle, the edge of the specimen is peeled off, which is more apparent at the junction of the fracture surface and the edge of the specimen.

It is detectable that no obvious tensile crack is produced in the specimens except for the specimen with a crack angle of $90^\circ$ during the test, and the ends of the prefabricated cracks in the fine sandstone specimen form through-tension cracks, causing the collapse of the prefabricated crack area as demonstrated in Figures 6 and 7. The fracture surface of the medium-fine sandstone specimen also produces unpenetrated tensile fractures, as presented in Figure 7. This issue is essentially attributed to the fact that the sandstone has a certain brittleness, so neither the fine sandstone nor the medium-fine sandstone specimens have obvious tension cracks. Since the constituent particles of the medium-fine sandstone are larger than those of the fine sandstone, their internal pores would be more. If the large particles contain microcracks, it is more likely to cause cracks in the
specimen. However, when the particle size is larger, the bonding contact area between particles is smaller, and the ability to resist external force deformation is weaker. Therefore, the medium and fine sandstone specimens are more prone to cracks than the fine sandstone specimens, but the specimens will be destroyed before the cracks extend through the specimens (Figures 6D and 7D).38 For the specimens...
with crack angles of 0°, 30°, and 60°, the tensile crack has not yet started to propagate before the failure of the specimen due to the low strength of the specimens. The main reason behind this fact is that the crack initiation pressures of the fine sandstone and medium-fine sandstone are different, and the pressure exerted on the specimens close to the failure mode does not reach the pressure corresponding to

**FIGURE 5** The stress–strain curves of the cracked sandstone specimens with different angles (medium-fine sandstone). (A) Stress strain curve (B) 0° (C) 30° (D) 60° (E) 90°
the crack initiation. This fact results in no apparent tension cracks and other nonsection cracks in various sandstone specimens with the same prefabricated fracture angle.

4 | DISCUSSION

4.1 | Evolution of the irreversible axial and lateral strains

The specimen deforms under the action of the external load. When the load is removed, the specimen still retains a certain irreversible deformation, which makes it unable to return to the original state, and finally exhibits plastic properties. By considering the axial deformation during the cyclic loading and unloading test as an example, the basics of the irreversible deformation calculation have been illustrated in Figure 8.

\[ d\varepsilon^{\text{irr}}_{m(n)} = \varepsilon^{\text{irr}}_{i+1} - \varepsilon^{\text{irr}}_i, \]  

(1)

where \( \varepsilon^{\text{irr}}_{m(n)} \) denotes the irreversible strain during a single loading and unloading cycle, and \( n \) represents the serial number of that cycle.

Therefore, the axial and lateral irreversible strains can be calculated using the superposition technique as follows:

\[ \varepsilon^{\text{irr}}_w = \sum_{1}^{N} d\varepsilon^{\text{irr}}_{w(n)}, \]  

(2)

where \( d\varepsilon^{\text{irr}}_{w(n)} \) represents the cumulative axial or lateral irreversible strains during each loading and unloading cycle, \( N \) denotes the total number of cycles, \( \varepsilon^{\text{irr}}_w \) represents the total irreversible strain, and \( w = 1, 2, \) or 3.

As shown in Figure 9, Equations (1) and (2), the strain change law of the specimen during the test can be evaluated using Equations (1) and (2). Figure 9A1–A4
and 9B1–B4 are the graphs associated with the strain variation of the fine sandstone and medium-fine sandstone specimens during cyclic loading and unloading tests, respectively. According to Figure 9, for both the fine sandstone and medium-fine sandstone specimens, the magnitudes of $\varepsilon_1^{\text{irr}}$, $\varepsilon_2^{\text{irr}}$, and $\varepsilon_3^{\text{irr}}$ first decrease and then increase gradually, and their corresponding plots exhibit a sudden increase or decrease when the specimen breaks. This is because, in the initial stage of cyclic loading and unloading, the internal pores and cracks of the specimen are compacted; therefore, the irreversible deformation in the first cyclic loading and unloading period is relatively large. When the specimen is compacted, the deformation of the specimen becomes larger and larger during the test.

The axial irreversible strains of the fine sandstone and medium-fine sandstone specimens show the same variation law. With the increase of the crack angle, the deformation of the specimen is larger during the failure. The deformation of the fine sandstone specimens in the $\sigma_2$-direction is relatively large as the failure occurs, and the irreversible strain of the fine sandstone specimens decreases gradually with the growth of the crack angle. However, the irreversible strain of the medium-fine sandstone gradually increases, and the deformation of

---

**Figure 7** The failure modes of medium-fine sandstone specimens with different angles (A) 0° (B) 30° (C) 60° (D) 90°.

**Figure 8** Schematic diagram of the calculations associated with the irreversible deformation.
FIGURE 9  Evolution of both axial and lateral irreversible strains of the cracked specimens for various specimens and a different number of cycles: (A) fine sandstone, (B) medium-fine sandstone; (A1, B1) axial and lateral irreversible strains as a function of cycles, (A2, B2), (A3, B3), and (A4, B4) in order present the irreversible strains $\varepsilon_1^{\text{irr}}$, $\varepsilon_2^{\text{irr}}$, and $\varepsilon_3^{\text{irr}}$ in terms of the number of cycles.
The relationships between the damage variables represented by the irreversible strains for sandstone specimens with different crack angles. (A) Fine sandstone (B) Medium-fine sandstone
the medium-fine sandstone specimens with crack angles of 0°, 30°, and 60° is not apparent. The irreversible strains of the fine sandstone and medium-fine sandstone specimens in the $\sigma_3$ direction show significant differences. The fine sandstone samples are always in a state of compression before failure, and the expansion phenomenon is not obvious. The medium-fine sandstone specimen expands considerably during the test, and with the increase of the upper limit of loading, the volume expands more and more until the specimen fails. Additionally, the irreversible strain of the fine sandstone specimens and the medium-fine sandstone specimens generally lessen with the growth of the crack angle.

Regarding fine sandstone and medium-fine sandstone, the dimension of composition particle of the medium-fine sandstone is larger; however, microcracks are inclined to exist in large particles. There are also more intergranular pores in the medium-fine sandstone, and the microcracks in the specimen are more likely to expand in the course of the loading. Under the action of external load, the phenomenon of stress concentration is formed between the particles composed of medium and fine sandstone, which induces the expansion of cracks inside the particles. During the experimentation, the deformation process of the medium-fine sandstone specimen is more noticeable.

4.2 Damage evolution based on the irreversible strains

To reflect the progressive damage process of the sandstone specimen in the cyclic loading and unloading stage before failure, the equivalent irreversible strain is utilized. This factor is capable of describing the irreversible strain variation laws associated with directions of the three principal stress in the true triaxial loading and unloading test. The equivalent irreversible reaction can be calculated as follows\textsuperscript{39}:

$$
\varepsilon_p = \sum_{i=1}^{n} (d\varepsilon^i_{1,\text{irr}})^2 + (d\varepsilon^i_{2,\text{irr}})^2 + (d\varepsilon^i_{3,\text{irr}})^2,
$$

where $i$ denotes the number of cycles, and $d\varepsilon^i_{1,\text{irr}}$, $d\varepsilon^i_{2,\text{irr}}$, and $d\varepsilon^i_{3,\text{irr}}$ in order represent the incremental of the irreversible strains ($\varepsilon^i_{1,\text{irr}}$, $\varepsilon^i_{2,\text{irr}}$, and $\varepsilon^i_{3,\text{irr}}$) in each cycle associated with the three principal stress directions.

When a rock fails, a sizeable irreversible strain is generated in the direction in which the stress is exerted. Therefore, the normalized irreversible strain can be utilized to describe the damage evolution\textsuperscript{40,41}:

$$
D_y = \frac{\sum_{i=1}^{n} (d\varepsilon^i_{y,\text{irr}})^2}{\varepsilon^i_{y,\text{irr}}}.
$$

where $D_y$ ($0 \leq D_y \leq 1$, $y = 1, 2, 3$) denote the damage variables pertinent to the maximum, intermediate, and minimum principal stress directions, respectively, $p$ is the number of cycles, $\varepsilon^i_{y,\text{irr}}$ represents the cumulative irreversible strains from the first cycle to the latest completed one for $y = 1, 2, 3$.

As demonstrated in Figure 10, the $D_1$, $D_2$, and $D_3$ variation laws of sandstone specimens with various angles are similar. The $D_1$ exhibits a linear relationship as a function of $\varepsilon_p$, whereas the relation between $D_2$, $D_3$, and $\varepsilon_p$ is approximately presented by a quadratic function relationship. Figure 10A1,B1 show that the damage degree ($D_y$) caused by the axial stress increases uniformly with the damage failure ($\varepsilon_p$) of the specimen. The slope of the fitting curve reflects the variation law of the damage degree due to the exertion of the axial stress on the specimen. The larger the slope, the smaller the damage caused by the axial stress to the specimen with the same damage degree of different crack angles. From the $D_1$-$\varepsilon_p$ curves of the specimens with the crack angles of 30°, 60°, and 90°, it can be observed that the larger the angle, the smaller the slope of the fitting curve. Furthermore, the values of $D_2$ and $D_3$ vary as a function of $\varepsilon_p$ in a quadratic manner for both fine and medium-fine sandstones.

4.3 Characteristics of the energy evolution for hysteresis loop

The hysteretic loop formed by the loading and unloading stress-strain curves during the cyclic loading and unloading of the rock is caused by its heterogeneity, and each hysteresis loop represents the energy dissipated in the stress cycle.\textsuperscript{42} The relationship between the energy forming a hysteresis loop and the number of cycles during the test has been presented in Figure 11. As shown in Figure 11, the energy evolution laws of the hysteresis loop of the fine sandstone and medium-fine sandstone specimens as a function of the number of cycles for different crack angles are the same. This is basically consistent with the irreversible strain change law during the cyclic loading and unloading of the specimen. With an increase in the crack angle, the energy of the last hysteresis loop of each specimen magnifies sequentially, indicating the level of the dissipated energy when the sandstone specimens of
various crack angles are broken. This issue also explains a particular feature: the larger the crack angle is, the higher the strength of the specimen is.

4.4 Damage evolution based on the irreversible strains and accumulated dissipated energy in each hysteresis loop

The irreversible strain change reflects the deformation and failure law of the specimen, and the energy dissipation accompanying the deformation process is closely related to the deformation of the specimen. The equivalent irreversible strain and the energy dissipation accumulated in the hysteresis loop can be selected to analyze the damage and failure process of the specimen. Where $D_h$ is defined as follows:

$$
D_h = \frac{\sum_{x=1}^{n} |\mu_x^h|}{N} 
$$

where $D_h$ is the dissipated energy at the $x$th hysteresis loop. $N$ represents the number of complete loading and unloading cycles experienced by the sample before failure. $n$ represents the current loading and unloading cycle, $n \leq N$.

The damage evolution law of fine sandstone and medium-fine sandstone specimens is shown in Figure 12. The damage degree of the sample varies with the number of cycles as a quadratic function. The obtained results indicate that the crack angle has a considerable influence on $\varepsilon_p$ and $D_h$, and there exist significant discrepancies between these values for fine sandstone and those for the medium-fine sandstone. For the specimens that have experienced the same number of loading and unloading cycles, the damage fitting curve of the specimen with a larger crack angle is commonly placed higher than the damage curve of the specimen with a smaller crack angle. This issue demonstrates that the specimen with a larger crack angle has a greater degree of damage during a single cycle of loading and unloading. The position of the fitting curves for the specimens with the crack angle of 0°, 30°, and 60° (see Figure 1A12,A2) and 0°, 30°, 60°, and 90° (see Figure 12B2) can reflect this feature. Figure 12B1 shows a special phenomenon dissimilar to the above-mentioned characteristics. The graphed results reveal that the damage fitting curve of the specimen with a small crack angle is usually higher than that of the specimen with a larger crack angle. For sandstone specimens with different crack angles, the evolution characteristics of $D_h$ in terms of the number of cycles are similar, and $\varepsilon_p$ exhibits obvious discrete characteristics.

Based on the discussion provided above, the index $\varepsilon_p$ comprehensively considers the damage caused by the three-dimensional stress to the specimen. Especially in the initial stage of the test, due to the small difference between the axial stress and the lateral stress, the share of the caused damage by the lateral stress is usually greater than that by the axial stress. The damage caused by the lateral stress cannot be ignored compared with the overall damage degree of the specimen, resulting in a considerable discrepancy in the damage degree at the initial stage of loading. The energy dissipation can be mainly interpreted by the $D_h$ index when the specimen is acted upon by damage and reflects the total energy dissipated during the damage process of the specimen.
Hence, this factor can better reflect the overall damage trend of the specimen. Choosing appropriate indexes is more advantageous to guide engineering construction.

5 | CONCLUSIONS

In this study, cyclic loading and unloading tests were carried out on both fine and medium-fine sandstone with different crack angles. The change law of the damaged specimen during loading and unloading was analyzed. Based on the current analysis, the following conclusions can be drawn:

(1) Under the condition of true triaxial cyclic loading and unloading, both fine sandstone and medium-fine sandstone show brittleness characteristics; nevertheless, the fine sandstone is stronger than the medium-fine sandstone. The fine sandstone specimen exhibits non-ideal elastic characteristics, and its stress–strain curve is somehow stepped, and the stress–strain curve of the medium-fine sandstone specimens has characteristics of a typical stress–strain curve. Further, the strength of the fine sandstone specimens with the same crack angle is higher than that of the medium-fine sandstone specimens.

(2) The fine sandstone and medium-fine sandstone specimens are mainly shear damaged, and the internal fractures of the medium-fine sandstone specimens are more likely to expand, indicating that the size of the sandstone composition particle has an influence on its own properties.

(3) During the test, the expansion phenomenon of fine sandstone specimens is not obvious, while the expansion phenomenon of medium-fine sandstone
specimens is significant. Based on the damage degree analysis of the specimen caused by the axial and lateral stress directions, it was observed that the damage degree caused by the axial stress increases linearly with the induced damage in the specimen, however, the caused damage due to the lateral stress to the specimen varies in terms of the specimen failure as a quadratic function.

(4) During the experimentation, the energy dissipation of the hysteresis loop can be related to the specimen strength. Its evolution law provides a crucial reference for predicting the damage degree of rock under the action of the cyclic disturbance. It is more conducive to examining the damage degree of rock in the early stage of cyclic disturbance based on the equivalent irreversible strain index.

ACKNOWLEDGEMENTS
This study was jointly supported by the National Natural Science Foundation of China (grant number 51974042), the Major Special Projects of Science and Technology in Shanxi Province (grant number 2019101015).

CONFLICT OF INTEREST
The authors declare no conflict of interest.

ORCID
Huarui Hu http://orcid.org/0000-0003-3131-1904
Binwei Xia http://orcid.org/0000-0002-8928-0461

REFERENCES
1. Zhou X, Qian Q, Yang H. Rock burst of deep circular tunnels surrounded by weakened rock mass with cracks. Theor Appl Fract Mec. 2011;56(2):79-88.
2. Wang Y, Gao S, Li C, Han J. Investigation on fracture behaviors and damage evolution modeling of freeze-thawed marble subjected to increasing-amplitude cyclic loads. Theor Appl Fract Mec. 2020;109(2):102679.
3. Hu H, Xia B, Luo Y, Peng J. Energy characteristics of sandstones with different crack angles under true triaxial cyclic loading and unloading. Energy Sci Eng. 2022;10(4):1418-1430.
4. Niu W, Feng X, Feng G, et al. Selection and characterization of microseismic information about rock mass failure for rockburst warning in a deep tunnel. Eng Fail Anal. 2022;131:105910.
5. Yang D, Hu J, Zhou T, Ding X. Cross-scale characteristics of damage evolution in granite under high-confining pressure cyclic loading. Int J Geomech. 2022;22(2):04021286.
6. Guo S, Sheng Qi. Numerical study on progressive failure of hard rock samples with an unfilled undulate joint. Eng Geol. 2015;193:173-182.
7. Zhang P, Li X, Li N. Strength evolution law of cracked rock based on localized progressive damage model. J Cent South Univ Technol. 2008;15:493-497.
8. Lu Y, Gong T, Xia B, Yu B, Huang F. Target stratum determination of surface hydraulic fracturing for far-field hard roof control in underground extra-thick coal extraction: a case study. Rock Mech Rock Eng. 2019;52:2725-2740.
9. Li Y, Yang R, Fang S, et al. Failure analysis and control measures of deep roadway with composite roof: a case study. Int J Coal Sci Technol. 2022;9:2. doi:10.1007/s40789-022-00469-1
10. Chen D, Zhang Q, Xie S, et al. Combined support technology for main roadway passing through goaf: a case study. Energy Sci Eng. 2020;8:3925-3941.
11. Munoz H, Taheri A. Local damage and progressive localisation in porous sandstone during cyclic loading. Rock Mech Rock Eng. 2017;50:3253-3259.
12. Wang S, Li X, Du K, Wang S, Tao M. Experimental study of the triaxial strength properties of hollow cylindrical granite specimens under coupled external and internal confining stresses. Rock Mech Rock Eng. 2018;51:2015-2031.
13. Hu H, Xia B, Luo Y, Gao Y. Effect of crack angle and length on mechanical and ultrasonic properties for the single cracked sandstone under triaxial stress-loading-unloading. Front Earth Sci. 2022;10:900238.
14. Li D, Wang E, Kong X, et al. Damage precursor of construction rocks under uniaxial cyclic loading tests analyzed by acoustic emission. Constr Build Mater. 2019;206:169-178.
15. Chen W, Li S, Li L, Shao M. Strengthening effects of cyclic load on rock and concrete based on experimental study. Int J Rock Mech Min. 2020;135:104479.
16. Aleksandr S, Yaroslav O, Maksim N, Aleksandr A. Predicting fatigue strength of rocks by its interrelation with the acoustic quality factor. Int J Fatigue. 2015;77:194-198.
17. Peng K, Zhou J, Zou Q, Song X. Effect of loading frequency on the deformation behaviours of sandstones subjected to cyclic loads and its underlying mechanism. Int J Fatigue. 2020;131:105349.
18. Xia M. Simulation of rock mechanical behavior under cyclic loading using clump parallel-bond models. Geotech Geol Eng. 2019;37:2325-2333.
19. Wang Y, Feng W, Hu R, Li C. Fracture evolution and energy characteristics during marble failure under triaxial fatigue cyclic and confining pressure unloading (FC-CPU) conditions. Rock Mech Rock Eng. 2021;54:799-818.
20. Meng Q, Zhang M, Han L, Chen Y. Acoustic emission characteristics of red sandstone specimens under uniaxial cyclic loading and unloading compression. Rock Mech Rock Eng. 2018;51:969-988.
21. Liang Y, Li Q, Gu Y, Zou Q. Mechanical and acoustic emission characteristics of rock: effect of loading and unloading confining pressure at the postpeak stage. J Nat Gas Sci Eng. 2017;44:54-64.
22. Xiao F, Jiang D, Wu F, Chen J, Chen Bo, Sun Z. Effects of prior cyclic loading damage on failure characteristics of sandstone under true-triaxial unloading conditions. Int J Min Sci Tech. 2020;132:104379.
23. Zhou X, Qian Q, Yang H. Rock burst of deep circular tunnels surrounded by weakened rock mass with cracks. Theor Appl Fract Mec. 2011;56(2):79-88.
24. Wu T, Gao Y, Zhou Y, Li J. Experimental and numerical study on the interaction between holes and fissures in rock-like
materials under uniaxial compression. *Theor Appl Fract Mech*. 2020;106:102488.

25. Fu J, Zhang X, Zhu W, Chen K, Guan J. Simulating progressive failure in brittle jointed rock masses using a modified elastic-brittle model and the application. *Eng Fract Mech*. 2017;178:212-230.

26. Feng P, Dai F, Liu Y, Xu N, Zhao T. Effects of strain rate on the mechanical and fracturing behaviors of rock-like samples containing two unparallel fissures under uniaxial compression. *Soil Dyn Earthq Eng*. 2018;110:195-211.

27. Liu Y, Dai F, Dong L, Xu N, Feng P. Experimental investigation on the fatigue mechanical properties of intermittently jointed rock models under cyclic uniaxial compression with different loading parameters. *Rock Mech Rock Eng*. 2018;51:47-68.

28. Tiwari R, Rao K. Post failure behaviour of a rock mass under the influence of triaxial and true triaxial confinement. *Eng Geol*. 2006;84:112-129.

29. Tiwari R, Rao K. Physical modeling of a rock mass under a true triaxial stress state. *Int J Rock Mech Min*. 2004;41(3):433.

30. Wang G, Feng X, Yang C, Han Q, Kong R. Experimental study of the mechanical characteristics of jinping marble under multi-stage true triaxial compression testing. *Rock Mech Rock Eng*. 2022;55:953-966.

31. Taheri A, Zhang Y, Munoz H. Performance of rock crack stress thresholds determination criteria and investigating strength and confining pressure effects. *Constr Build Mater*. 2020;243:118263.

32. Panthee S, Singh P, Kainthola A, Das R, Singh T. Comparative study of the deformation modulus of rock mass. *Bull Eng Geol Environ*. 2018;77:751-760.

33. Song Z, Li M, Yin G, Ranjith P, Liu C. Rock strength criterion considering the effect of hydrostatic stress on lode angle effect. *Energy Sci Eng*. 2019;7:1166-1177.

34. Wu H, Wang Z, Wang C. The mechanism study of cracks propagation of different floor strata combinations under mining. *Geotech Geol Eng*. 2018;36:3743-3749.

35. Zhao K, Xiong L, Kuang Z, Xu Z, Zeng P. Uniaxial compression creep characteristics and acoustic emission characteristics of two different kinds of red sandstone with different particle sizes. *Arab J Sci Eng*. 2021;46:11195-11206.

36. Zhao H, Liu C, Zhang J, Ge L. Breakage behavior of gravel rock particles under impact force. *Comput Part Mech*. 2021;8:1075-1087.

37. Shah K, Hashim M, Emad MZ, Ariffin K, Khan N. Effect of particle morphology on mechanical behavior of rock mass. *Arab J Geosci*. 2020;13. doi:10.1007/s12517-020-05680-5

38. Song Z, Ji H, Zeng P, Sun L, Tan J. Phase-like transition characteristics of uniaxial compression failure of weakly cemented coarse-grained sandstone in Western China. *J Mining Saf Eng*. 2020;37(5):1027-1036. (in Chinese).

39. Gao Y, Feng F. Study on damage evolution of intact and jointed marble subjected to cyclic true triaxial loading. *Eng Fract Mech*. 2019;215:224-234.

40. Eberhardt E, Stead D, Stimpson B. Quantifying progressive pre-peak brittle fracture damage in rock during uniaxial compression. *Int J Rock Mech Min Sci*. 1999;36(3):361-380.

41. Qiu S, Feng X, Xiao J, Zhang C. An experimental study on the pre-peak unloading damage evolution of marble. *Rock Mech Rock Eng*. 2014;47(2):401-419.

42. Li C, Gao C, Xie H, Li N. Experimental investigation of anisotropic fatigue characteristics of shale under uniaxial cyclic loading. *Int J Rock Mech Min Sci*. 2020;130:104314.

43. Bagde M, Petro V. Fatigue properties of intact sandstone samples subjected to dynamic uniaxial cyclical loading. *Int J Rock Mech Min Sci*. 2005;42(2):237-250.

---

**How to cite this article:** Hu H, Xia B, Li Y, Luo Y, Peng J. Analysis of damage characteristics of fine and medium-fine cracked sandstones under a complex stress path. *Energy Sci Eng*. 2022;10:3443-3458. doi:10.1002/ese3.1230