Experimental research on the anisotropic properties of sandy slate

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Abstract. In this study, the effect of joint on the anisotropy of a homogeneous, stiff, and intact sandy slate from a typical hydropower station is investigated by selecting and making jointed rock samples with jointed angles of 0°, 30°, 45°, 60°, and 90°. Accordingly, an acoustic measurement and a triaxial compression test are conducted on these jointed rock samples. The research results show that the joint angle significantly influences the rock mass anisotropy. In other words, the average value of the longitudinal wave velocity of the jointed rock samples is smaller than that of the intact rock. Furthermore, the value of the longitudinal wave velocity increases with the increase of the joint angle and is the largest when its spreading direction is in line with the joint inclination. The stress–strain curve, elastic modulus, peak strength, and failure mode of the joint rock samples are found to have anisotropic features. The failure stage occurs in samples with joint angles of 0°, 30°, and 90°. The stress–strain curve of the samples with joint angles of 45° and 60° tends to be horizontal. Meanwhile, the elastic modulus and the compression strength displayed a U-shaped distribution with an increase of the joint angle and the smallest value that belongs to samples with joint angles of 30° and 60°. The peak value ratio of the elastic modulus and the compression strength gradually decrease when the confining pressure increases, indicating that the anisotropy of the samples has weakened (i.e., the increase of the confining pressure decreases the anisotropy of the sandy slate strength). The failure mode of the samples with different joint angles is presented as follows: the samples with a 0° joint angle exhibit a tensile splitting damage; the samples with a 90° joint angle exhibit compression–shear damage; the samples with a 30° joint angle exhibit the combination of slide and compression–shear damage; and the samples with 45° and 60° joint angles exhibit slide damage along the joint surface.

1. Introduction

Rock mass comprises the rock and the structural plane. Rock mass engineering shows different mechanical characteristics in all directions because of the structural plane [1–4]. A uniaxial compression test showed three failure modes of rock mass with a group of joints, and the joint angle variation was determined as the main reason for the strength and deformation anisotropy of the specimen [5]. Mixtures of plaster, cement, and water were used to make cylindrical columnar jointed specimens with different dip angles (i.e., ranging from 0° to 90°) for the performance of uniaxial compression tests to investigate the mechanical anisotropy of the columnar jointed rock mass. Consequently, the deformation modulus and the uniaxial compression strength of the columnar jointed specimens with different dip angles were obtained [6]. An experimental study on the deformation and strength characteristics of marble with joints showed that the specimen failure mode mainly depends on the angle between the joint plane and the maximum principal stress and is within the range of the...
test confining pressure, which had no effect on the specimen failure mode. The difference of the joint strength was found as the main reason for the difference in the failure strength of different specimens [7]. Experiments on the anisotropy of sandstone and slate were also conducted at the Lianghekou Hydropower Station. The results showed that the rock anisotropy is closely related to lithology, rock layer thickness, rock weathering, and degree of rock fissure development [8]. Tests on limestone and sandstone with a single weak surface were also performed. As a result, two main failure modes of the weak surface sample were observed: 1) the sample is damaged along the weak surface, and 2) the sample is not damaged along the weak surface [9]. Meanwhile, uniaxial and triaxial compression tests on the sericite and siliceous plate phyllite at the dam site of a hydropower station in Jinshajiang obtained the variation rule of the rock strength relative to its soft structural surface and the angle (location angle) of the loading principal compressive stress. The anisotropy index was used to quantitatively evaluate the anisotropy degree of phyllite [10]. The uniaxial and triaxial compression tests on five bedding angles (i.e., 0°, 30°, 45°, 60°, and 90°) were designed according to the common bedding sandstone in engineering. The results implied that the significant anisotropy of the bedding sandstone can be observed under the uniaxial and triaxial compression tests. The elastic modulus gradually increased, but some mechanical parameters (i.e., deformation modulus, compressive strength, cohesion, and friction angle) first decreased and then increased to exhibit a U-shaped curve as the bedding angle varied from 0° to 90°. The maximum value at 0° or 90° and the minimum value at 60° were reached [11]. The triaxial unloading tests on precasted rock samples of a single joint with different dip angles were conducted to investigate the anisotropic mechanical behavior of jointed rock masses under excavation, including the stress–strain curves, deformation and strength characteristics, and failure modes [12]. An MTS815-type programmable servo rigidity tester was used in high-temperature sandstone plates during the conventional triaxial compression test. The characteristics, deformation parameters, and strength of the specimen failure mode under various temperatures and bedding angles were then obtained based on the test result analysis. The anisotropic temperature effect of the layered sandstone was also discussed [13]. The triaxial compression test was conducted to study the anisotropic mechanical properties of sandstone under loading. The results showed that the compressive strength and the elastic modulus of the joint specimen were U-shaped with the joint dip angle, and the failure types of the joint rock mass were controlled by the joint surface and rock block strengths [14]. Triaxial compression tests were also performed on black shale with different bedding angles. Black shale is considered to have the characteristics of wave velocity and strength anisotropy and a failure mode that is related to the confining pressure condition and bedding plane angle [15]. Direct shear tests on a shale sample with different bedding angles were conducted to analyze the mechanical properties of bedding planes and the shear strength anisotropy. The causes for the shear strength anisotropy were also analyzed based on the anisotropy of the shear failure mechanisms and the concentration factor of the shear stresses [16]. A real-time, high-temperature triaxial stress permeability testing equipment was used to study the evolution of the anisotropic permeability of oil shale at different temperatures. Hence, the reasons for the permeability anisotropy in different bedding directions of oil shale at different temperatures have been discussed [17]. An anisotropic failure criterion was also proposed based on the Hoek–Brown failure criterion by introducing an anisotropic parameter associated with the microstructure tensor $a_{ij}$ and the loading directions $l_i$. Accordingly, the sensitivity of the parameters used in the anisotropic failure criterion was discussed. The proposed anisotropic failure criterion can describe the material strength variation in the function of the orientation of the sample related to the loading direction [18]. The anisotropic mechanical properties and the deformation failure modes of specimens were then analyzed under different loading conditions. Meanwhile, a numerical analysis was performed to study the failure modes and the mechanical mechanisms of slate slopes with different bedding plane angles. The results showed that the bedding planes in silty slates were weak surfaces that affect the mechanical properties of rock mass and contribute to the anisotropic characteristics of the silty slates [19]. The method for the dynamic fracture test and the notched semi-circular bend specimen were suggested using the split Hopkinson pressure bar system from the International Society of Rock Mechanics. The anisotropy of dynamic
fracture energy of Barre and Stanstead granite is also investigated. The dynamic fracture energy was found to be anisotropic for SG and BG. At a similar loading rate, the dynamic fracture energy in SG and BG along the X direction was minimum, while that along the Z direction was maximum [20]. A fracture path criterion considering the fracture energy anisotropy was proposed. Moreover, the influence of the fracture energy anisotropy on the hydraulic fracturing path was studied through finite element simulations with the criterion considered in the cohesive elements. The study indicated that the fracturing energy anisotropy is a dominant factor limiting the hydraulic fracture propagation. In other words, the ratio of the fracturing energy perpendicular to the bedding in different rocks is limited [21].

Although existing studies have drawn some useful conclusions, current research on the anisotropy of jointed rock masses has mainly focused on soft and harder rocks, and research on the anisotropy of hard rock is still relatively few.

The present study selects sandy slate as the research object and prefabricates its artificial joint. The longitudinal wave velocity and triaxial compression tests are performed to investigate the anisotropic mechanical properties of sandy slate. The results reveal the anisotropy of the mechanical parameters, such as the deformation and strength characteristics of sandstone, which provides an excellent basis for solving practical engineering problems.

2. Sample preparation and test scheme

2.1. Sample preparation

The sandy slate from an excavated slope at the Lianghekou Hydropower Station on Yalong River in Sichuan was selected and made into a complete sample and a joint sample with 50 mm diameter and 100 mm height according to the test procedures. The sandy slate had few natural joints. The rock sample had a uniform hard texture and a good integrity. Therefore, a single through joint was manually prefabricated. The joint dip angles are represented by $\beta$ herein (i.e., 0°, 30°, 45°, 60°, and 90°).

The joint specimens were prepared as follows:

(1) Complete cylindrical specimens were prepared.

(2) The specimens were placed in a special jig, fixed at an angle to the blade, and cut with a cutter.

(3) The two halves of the specimen were cut with gypsum bonding (3:1 gypsum and water ratio) and removed after 48 h solidification. The surface was then smoothened.

The test rock samples from the same group were taken from a single intact rock mass to avoid the dispersion of the test results due to lithological inhomogeneity. The samples were preliminarily screened before the test. First, the rock samples with similar colors and textures were selected, and those with surface damage and visible cracks were removed. Figures 1 and 2 illustrate the prepared rock samples.

Figure 1. Complete sample

Figure 2. Joint specimens

2.2. Test scheme
The longitudinal wave velocities of the complete and joint samples were measured. The abnormal sample was removed. Subsequently, the wave velocity rule between different joint samples was analyzed. The triaxial compression test was performed using the RMT-150C testing machine developed by the Institute of Rock and Soil Mechanics, Chinese Academy of Sciences. First, the confining and axial pressures were applied synchronously to the predetermined value (i.e., 5 MPa, 10 MPa, 20 MPa, and 30 MPa) at loading rates of 0.1 MPa/s and 0.2 KN/s, respectively, through stress control. During this time, the sample was in a hydrostatic pressure state. Next, the displacement control method was used to keep the confining pressure unchanged during the test. The displacement loading rate was 0.005 mm/s. The axial load was applied until the specimen was damaged. The total stress–strain curve of the specimen under the triaxial compression test was then obtained.

3. Formatting the text

3.1. Acoustic wave velocity testing

The compressional wave velocities of the complete and joint samples were tested, with 24 samples in each group. The average wave velocity of each group was also calculated. Table 1 presents the test results. Figure 3 depicts the relationship between the average wave velocity and the joint angle.

| Joint Angle (°) | Complete | 0° | 30° | 45° | 60° | 90° |
|----------------|----------|----|-----|-----|-----|-----|
| Average value  |          | 4866 | 4335 | 4486 | 4718 | 4773 | 4800 |
| Minimum value  |          | 4192 | 3423 | 3493 | 4268 | 4423 | 4253 |
| Maximum value  |          | 5176 | 4930 | 4876 | 5179 | 5091 | 5073 |

Figure 3. Relationship between the compressional wave velocity and the joint angle

The results showed that the average compressional wave velocities of the joint specimens were all smaller than those of the complete specimens. The sand–slate joint specimens showed an obvious wave velocity anisotropy, and their compressional wave velocity increased with the joint angle increase. The variation of the compressional wave velocity with the joint angle showed that the wave velocity reached its maximum value when the joint and the acoustic wave traveled in the same direction.

3.2. Stress–strain curve analysis

Figure 4 displays the stress–strain curves for the complete and joint sandy slate samples. The results showed that the stress–strain curve of the complete sample did not have a compression stage because of the tight bonding of the sample. On the contrary, the joint sample had a compression stage because of the presence of gypsum. The total deformation of the joint sample, which is the superposition of the rock and filling material deformations of the jointed surface, was greater than that of the complete sample.
sample. The results also showed that the complete sample specimen’s resistance to deformation was enhanced, and its compressive strength increased with the increase of the confining pressure level. The confining pressure level greatly influenced the specimen’s yielding process, which was short under a low confining pressure. The stress rapidly dropped, and the specimen suddenly broke after reaching the peak strength. The confining pressure was between 20 MPa and 30 MPa after the peak strength of the sample was reached. Accordingly, a longer stage of strain increase was observed. The yield characteristics of the sample became more significant as the confining pressure level increases. In addition, the shape of the stress–strain curve of the joint samples was greatly affected by the joint angle. A failure stage existed in the joint samples with 0°, 30°, and 90° dip angles, whereas no failure stage appeared in the joint samples with 45° and 60° dip angles. The stress–strain curve tended to be horizontal, which was related to the failure mode, when the peak value was reached.

![Stress-strain curves of intact and jointed specimens](image)

**Figure 4.** Triaxial compression stress–strain curves of the intact and jointed specimens
The stress–strain curve of the joint specimen with a 30° angle of inclination was observed. The curve showed an obvious drop in the compaction stage. The stress suddenly dropped and then continued to rise until the specimen was damaged. The stress–strain curve’s sudden drop section under a 20 MPa confining pressure was enlarged (Figure 5). The axial strain still increased when the stress dropped. When the test was stopped, and the sample was removed, the gypsum surface was crushed, and traces of friction and sliding were found on the upper and lower parts of the sample. Therefore, the stress drop was considered to be caused by the gypsum failure and sliding on the joint surface. Since then, the upper and lower parts of the sample continued to bear the load under the action of friction due to the confining pressure restraint. The stress–strain curve continued to rise, and the rock block was finally damaged.

![Figure 5](image)

**Figure 5.** Enlarged view of the descending stage of the 30° joint specimen under a 20 MPa confining pressure

### 3.3. Analysis of the deformation characteristics

The deformation of the joint specimens should be the superposition of the rock and filler material deformations at the jointed surface. The elastic modulus obtained in this test is the combination of the two deformations. The joint angle greatly influenced the elastic modulus of the joint specimen. Figures 6 and 7 depict the variation curve of the elastic modulus with the joint angle. The results showed that under different confining pressure levels, the elastic modulus of the joint specimens changed to a U shape as the joint angle increased. The failure of the 30° joint sample involved both slip failure along the joint surface and the pressure–shear failure across the joint surface, which produced large strains and small deformation parameters. Hence, the reason for the minimum value of the elastic modulus at the 30° joint angle was related to the failure mode of the 30° joint specimen. Moreover, with the increase of the confining pressure, the ratio of the maximum and the minimum of the elastic modulus gradually decreased under the same confining pressure level. These results indicate that the confining pressure reduced the deformation difference of the joint samples, and the existence of the confining pressure weakened the deformation anisotropy of the joint samples.
3.4. Peak strength analysis

Table 2 is a statistical table of the peak strength of different joint angles under different confining pressures. Figure 8 illustrates the relation curve between the peak intensity and the joint angle. The results showed that the joint angle significantly affected the triaxial compressive strength value of the joint specimen. The triaxial compressive strength of the joint specimen changed into U shape with the joint angle. Under the same confining pressure conditions, the compressive strength exhibited a trend of decreasing first and then increasing. Except for the confining pressure of 0 MPa, the compressive strength of the 90° joint sample was the largest, and the minimum value appeared at the 60° joint angle. Figure 9 shows that the ratio of the maximum and minimum values of the compressive strength gradually decreased with the increase of the confining pressure. A comparison of the ratios of the maximum and minimum values of the peak strength under different confining pressures showed that the difference in the compressive strength of the specimens with different joint obliquities weakened. In other words, the increase of the confining pressure reduced the strength anisotropy of the sandy slate.

| Joint angle | Confining pressure | 0   | 5   | 10  | 20  | 30  |
|-------------|--------------------|-----|-----|-----|-----|-----|
| 0°          | 0MPa               | 112.237 | 99.124 | 118.787 | 223.932 | 241.848 |
| 30°         | 5MPa               | 109.191 | 135.403 | 193.067 | 216.624 | 256.017 |
| 45°         | 10MPa              | 13.415  | 24.43  | 51.337 | 76.131 | 84.465 |
| 60°         | 20MPa              | 23.238  | 21.537 | 35.121 | 43.066 | 61.981 |
| 90°         | 30MPa              | 76.366  | 145.754 | 187.693 | 306.65 | 315.755 |

Table 2. Peak strength in the triaxial compression test of the sectioned specimens
3.5. Strength parameter analysis

Table 3 presents the statistical values of the strength parameters of the joint specimens. Figures 10 and 11 illustrate the relationship between the shear strength parameters and the joint inclination. The results showed that the strength parameters of the joint specimens were all smaller compared to those of the complete specimens. The parameters of the 90° specimen were the largest and closest to those of the complete specimens. The cohesion force and the internal friction angle of the 60° specimen were the smallest. Furthermore, the cohesive force and the internal friction angle were U-shaped with the joint angle. The ratio of the maximum and minimum cohesions of the joint samples was 2.78. The ratio of the maximum and minimum internal friction angles was 4.15. Therefore, the strength parameters of the joint samples were anisotropic.

| Strength parameters | Complete | 0°  | 30° | 45° | 60° | 90° |
|---------------------|----------|-----|-----|-----|-----|-----|
| $c$/MPa             | 19.74    | 13.83 | 11.11 | 7.09 | 6.58 | 19.70 |
| $\phi$ (°)          | 47.90    | 46.40 | 30.20 | 23.30 | 11.50 | 47.70 |

Figure 10. Relationship between the cohesion and the joint orientation  
Figure 11. Relationship between the internal friction angle and the joint orientation

3.6. Damage feature analysis

Figure 12 depicts the specimen failure modes with different joint inclinations under the triaxial compression test. The results showed that the joint surface of the 0° joint specimen was dominated by the tensile splitting failure, while that of the 90° joint specimen was dominated by the compression—
shear failure. In addition, the failure form of the 30° joint specimen was mainly compression–shear failure. A large amount of gypsum powder was extruded from the joint position of the sample, indicating that the sample slid along the joint surface during the loading process. When the stress–strain curve was combined, the 30° joint specimen was considered as the joint surface mixed failure mode of slip and compression–shear failures. The failure modes of the 45° and 60° joint samples mainly slid along the joint surface. The bonded gypsum was broken and dislocated, and the extrusion marks of gypsum were observed near the joint surface.

![Joint Sample Images](image1.png)

**Figure 12.** Failure diagram of the joint sample

### 4. Conclusions
This study made a single through joint specimen using the sandy slate from an excavated slope of the Lianghekou Hydropower Station on Yalong River in Sichuan. The anisotropic mechanical properties of the sandy slate were studied through acoustic and triaxial compression tests. Consequently, the results showed that the prefabricated jointed sandy slate exhibited an anisotropic wave velocity. The compressional wave velocity of the joint specimens was smaller than that of the complete specimens and gradually increased with the joint angle increase. The wave velocity was the largest when the joint was in the same direction as the sound wave. Moreover, the stress–strain curve, elastic modulus, and peak strength of the prefabricated jointed sandy slate exhibited anisotropy. The stress–strain curve for the joint specimens with different joint angles had a large difference in shape and corresponded to its failure form. The elastic modulus and the peak strength of the jointed specimens showed a U-shaped distribution with the increasing joint angle. With the increase of the confining pressure level, the difference in the deformation and the strength between the samples with different joint angles decreased with the degree of anisotropy. In addition, the failure forms of the jointed samples can be divided into three types: 1) shear failure across the joint plane; 2) sliding failure along the joint plane; and 3) mixed failure superposition by sliding failure along the joint plane and shear failure.
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