Study on mechanical properties of a layered rock with holes under the support structure

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Abstract

In order to analyze the action mechanism of the tunnel support structure and its supporting characteristics in a layered and weak rock tunnel, an experimental study on seven types of support situations, namely, rough tunnel, systematic rock bolt support, systematic rock bolt, and shotcrete support, systematic rock bolt and shotcrete and steel arch support, steel pipe support, steel pipe, and shotcrete support, and steel pipe and shotcrete and steel arch support, has been conducted. The mechanical, deformation, and support characteristics of the rock with holes under uniaxial compression tests have been studied. The experimental results demonstrated that (1) all different support structures can enhance the uniaxial compressive strength of the specimens, but different support structures exhibit different effects. The rock bolt can significantly enhance the strength of the specimen, but the supporting effect of concrete and steel arches is not evident. (2) The bedding direction directly affects the strength enhancement of the support structure to the specimen, the support strength of the support structure to the rock with a bedding angle of 90° is higher than that of the rock with a stratification angle of 0°, and the bedding affects the failure process of the rock mass and the secondary crack distribution. (3) By using the CT scan of the specimens after the test, it is found that the bolt's crack arrest effect on cracks is the result of weakening, shearing, and arresting of cracks in the anchorage zone; the crack arrest effect is related to the size of the anchorage zone, and the larger the range of the anchorage zone, the better the crack arrest effect.

NOMENCLATURE

Radial stress

Tangential stress

Shear stress

Vertical stress

Horizontal stress coefficient

, Radius

Radial distance

Angle

Radial stress

, Tangential stress

Radial displacement

Shear modulus of elasticity

, Support pressure

Dimensionless length

Elastic modulus

Poisson's ratio

Thickness

Displacement

1 INTRODUCTION

The engineering practice shows that the disturbance of tunnel excavation changes the stress state of the surrounding rock and causes the deformation of the surrounding rock. If the surrounding rock deformation is not controlled by constructing a support structure, it will often be difficult to stabilize the surrounding rock of the tunnel.[1] In fact, after the continuous accumulation of engineering experience, theoretical study, and experimental research, the modern tunnel support theory has reached a consensus, that is, the tunnel is a structure that integrates load, material, and structure.[2] The surrounding rock of the tunnel is the primary source of the load borne by the support structure, and it also shows a certain bearing capacity. In the process of diagenesis, there are great differences in the physical fields such as stress, groundwater, and temperature, which lead to different properties of the rock and the soil, and the mechanical response will significantly vary after being disturbed by tunnel excavation. Developing the corresponding excavation methods and support plans for different types of the surrounding rock is considered an effective and controllable measure to control the deformation of the surrounding rock and ensure the stability of the surrounding rock of the tunnel.

The supporting mechanism of the support structure, the interaction relationship between the surrounding rock and the support structure, the selection of the timing of support, and the supporting effect of the support structure under different surrounding rocks have been the focus of researchers around the world, [3-8] among them the action mechanism of the support structure is considered to be particularly complex. The bolt is considered a very effective support system in tunnel engineering. Although bolts are widely used, the supporting mechanism of bolts has not been clearly identified. There are many kinds of bolts for tunnels, among them, the most commonly used are systematic rock bolts and steel pipes. Because of their grouting function, steel pipes are often used to support or treat weak–broken surrounding rocks. Sometimes when the tunnel excavation has a great impact on the shallow surface, steel pipes are often used for grouting the surface or the slope. The systematic rock bolts are mostly used for the initial support of tunnels. However, the existing support theories mostly investigate the support effect of systematic rock bolts[9-11] and rarely use the support mechanism of steel pipes. Investigating the action mechanism of systematic rock bolts and steel pipes is considered the basis of understanding their supporting effect on surrounding rocks. Yanyi Yang [12,13] studied the anchoring effect and the mechanism of systematic rock bolts on the layered rock mass and proposed the constitutive relationship of the anchored layered rock mass. He also pointed out that the bolt induces a toughening and crack arrest effect on rock fractures, which thus reduces the damage of the rock mass and improves the strength of surrounding rocks. Yang et al [14,15] used the anchored layered rock mass as the equivalent continuous medium and derived the constitutive equation of the anchored layered rock mass. According to the analysis of the formula, it is believed that the reinforcement effect of bolts on the jointed rock mass primarily improves its shear strength and the deformation capacity of joints. Zhang et al [16]believed that the anchored rock bolts work together with the surrounding rocks, and the bolt and the fractured rock mass reinforced by the bolt can be considered as a damaged cylindrical bolt element, which along with the surrounding damaged rock mass forms an anchoring damaged rock mass element. During calculation, the stiffness of the cylindrical bolt element is added to the stiffness matrix of the corresponding damaged rock mass element in order to reflect the confinement effect of the bolt on the deformation of the surrounding rock. Yang et al[17] studied the deformation process of the anchoring body of a layered rock by using laboratory experiments and concluded that the anchoring effect of bolts on the layered rock mass primarily improves the post-peak bearing capacity of the anchoring body and the toughness of the anchoring layer and induces little influence on the pre-peak mechanical properties. Wang et al [18] believed that the existence and changes in the seepage pressure and fractures change the damage characteristics of the rock mass, and its stiffness decreases during the deformation process, whereas the bolts can improve the mechanical and damage characteristics of the rock mass; this improves its stiffness. They proposed the solution by using the concept of added stiffness to reflect the anchoring effect of the bolt on the fractured rock mass. Wei Zhang and Quansheng Liu [19-21]have reported a comprehensive and systematic summary of the existing theories of rock bolt reinforcement in the jointed rock mass and pointed out that the study of the anchoring mechanism of the deep fractured rock mass should collectively consider all factors, such as the effect of the actual engineering application, the behaviors of the anchored rock mass, the effect of anchoring components, etc. Zhang et al[22,23] studied the mechanical characteristics and failure features of the bolt-supported jointed rock mass by using the bolt reinforcement tests on the rock mass with pre-existing flaws in the laboratory. In order to solve the problem of the anchoring mechanism of the rock and the soil, international scholars have also carried out a lot of research work, primarily by applying the following two aspects:[22,24-32] the load transfer mechanism of bolts and the anchoring effect of bolts, by using methods such as laboratory simulation, theoretical analysis, in-situ field test, etc., and the research results have enriched and deepened the understanding of the reinforcement mechanism of bolts on the rock and soil structure.

Therefore, similar simulation materials were used to form anchored specimens with pre-existing holes. Then, laboratory uniaxial compression tests and CT scan were carried out to study the strength, deformation characteristics, and crack propagation laws. The numerical simulation method is used for the coupled stress-damage simulation of fracturing in the rock. By the analysis of different supporting characteristics, in this paper, we investigate the supporting mechanism of support structures on the layered and weak rock tunnel, which provides a theoretical basis for field application.

2 EXPERIMENTAL PREPARATION

2.1 Specimen preparation

The specimens are made of the common C15 cement mixed with sand and quicklime, with a composition of C15 cement:sand:quicklime = 1:3:1.5. The coagulant is slaked lime, which is used in the same amount as cement. For the systematic rock bolt, the #45 steel is selected and processed into a threaded steel rod with a strength class of 8.8 (Figure 1(c)). The threaded rod shows a yield strength of 640 MPa, a tensile strength of 800 MPa, and a diameter of 5 mm. For the advancing conduit, it is made of the 45# carbon steel pipe (Figure 1(d)). The outer diameter of the steel pipe is 6 mm, and the wall thickness is 1 mm. The specimens of 100 mm $\times$ 100 mm $\times$ 100 mm were prepared through the cast-iron mold. During pouring, a steel tube with an outer diameter of 22 mm was placed in the middle of the test mold to reserve a round hole with a diameter of 20 mm. The specimen was poured in four times, with a thickness of 20 mm, 30 mm, 30 mm, and 20 mm, respectively. After the first three pourings, five bolts with a length of 25 mm and a diameter of 5 mm were evenly prepared along the round hole, as shown in Figure 1(a). The bedding structure is simulated by uniformly laid 100-mesh mica sheets with a thickness of 0.2 mm, and the bedding spacing is 20 mm. The prepared specimens were cured at room temperature for 28 days, and then they were used for laboratory uniaxial compression tests. For the size and the loading mode of specimens, refer to Figure 1(b).

2.2 Experimental plan

Seven types of support conditions, namely, rough tunnel, systematic rock bolt support, systematic rock bolt, and shotcrete support, systematic rock bolt and shotcrete and steel arch support, steel pipe support, steel pipe, and shotcrete support, and steel pipe and shotcrete and steel arch support, are considered. The shotcrete is simulated by using the epoxy resin with a thickness of 2 mm. The steel arch is composed of 304 stainless-steel pipes with an inner diameter of 20 mm. During the installation process, the steel pipe was put into the reserved cavity, and then the epoxy resin was injected into the pores between the outer wall of the steel pipe and the surrounding rock by using a syringe. Each support mode has been tested by the rocks with beddings angles of 0° and 90°, and the mechanical properties of the rock with holes and the failure of the surrounding rock under different support methods have been studied. In order to reduce the dispersion effects, three specimens were prepared for each case, and the ids and the support methods of the specimens are shown in Table 1.

The MTS815 rock mechanics testing system was used for the uniaxial compression tests of the anchored specimens with holes. The displacement control method was used as the loading type of the specimens, and the loading speed was controlled at 0.1 mm/min. During the test, a high-definition camera was used for recording the development and penetration of the surface cracks of the specimens, and the development process of the internal cracks in the holes was recorded by using the industrial endoscope apparatus.

Before and after the test, a German Siemens SOMATOM Scope X-ray Spiral CT Scanner was used to perform the non-destructive scanning of the specimens in order to detect the development and distribution of the internal cracks of the specimens. The spatial resolution of the CT scanner was 0.35 mm $\times$ 0.35 mm, the contrast resolution was 3 Hu, and the layer thickness was 0.75 mm.

3 EXPERIMENTAL RESULT ANALYSIS

3.1 Failure modes of the specimens with holes and anchors

For failure modes of the rock with holes and anchors under the uniaxial compression test, refer to Table 2.

According to different bedding angles, the failure modes of the macroscopic cracks are primarily the shear failure (with a bedding angle of 0°) and the tension failure (with a bedding angle of 90°). The macro-cracks of the specimens with a bedding angle of 0° started from the collapse of the two side walls of the hole and developed along an oblique diagonal line to the opposite corner, and finally, they formed the single macro-failure surface on both sides (P1–3 and PC1–1). If the shear cracks on both sides of the hole wall develop along the upper and lower corners of the hole wall to form through-cracks, the specimen will eventually show the type X-I (M1–1) or X-II conjugate shear failure (BC1 –2). There are also specimens that only formed through-cracks on one side of the hole wall, and the cracks on the other side did not develop or developed from the hole wall only along the loading direction to one end of the specimen, which shows an inclined T-shaped type I (B1–3, BC1–2, and PCG1–2) or an inclined T-shaped type II shear failure (BCG1–3). Without considering the secondary cracks of the specimens, the simplified diagram of morphologies of the above three master cracks is shown in Figure 2(a). The macro-cracks of the specimens with a bedding angle of 90° are primarily controlled by the vertical bedding. The specimens underwent tensile splitting along with the bedding under the action of load, and the cracks on the controlled failure surface started from the collapse of the two side walls of the hole and then developed toward one end (BC2–3) or both ends (M2–1, B2–3, BCG2–2, P2–1, PC2–1, and PCG2–1) of the specimen along the vertical bedding direction. The simplified diagram of the master cracks is shown in Figure 2(b).

According to different crack formation mechanisms, it can be divided into three types: tensile crack (T_fracture), shear crack (S_fracture), and far-field crack (R_fracture). Tensile cracks can be divided into two types: one type is distributed in the tensile stress concentration area at the top and bottom of the hole, and the other type is distributed along with the vertical bedding, which is caused by the tensile stress of the bedding. The shear cracks start in the compressive stress concentration areas on both sides of the hole and gradually develop into the distance under the continuous load. Such types of cracks in the specimens with a bedding angle of 0° often develop into controlled failure cracks. The far-field cracks are the cracks located far away from the area around the hole. The above three types of cracks may not appear on the same specimen at the same time, but, through the crack type labels of the specimens in Table 2, it is not difficult to find that the specimens with mainly shear failure, such as the specimens with a bedding angle of 0°, must have shear cracks (S_fracture). Similarly, the specimens with mainly tensile failure, such as the specimens with a bedding angle of 90°, must have tensile cracks (T_fracture).

3.2 Damage and destruction of holes

The failure modes of the specimens can be divided into three types: hole wall collapse, crack initiation and propagation, and surface peeling off. The degree of hole wall collapse is found to be different under different support conditions of the specimens (Figure 3); among them, the rough hole with a bedding angle of 90° has the most serious collapse (M2–3), and there is no hole wall collapse in the specimens supported by the bolts, concrete, and steel arches (BCG2–3). The walls of the holes under the bolt support (B1–3, B2–3, P1–3, and P2–1) still show different degrees of collapse and peeling, but the overall damage degree of these holes has been significantly improved as compared to that of the rough holes (M1–1 and M2–1). Under the support of bolts and concrete, the hole walls of the specimens do not peel off, and the holes of some specimens are compressed, thus resulting in lateral deformation (BC1–3 and BC2–3). It is foreseeable that without the support and the bonding effect of the simulated concrete layer, the integrity of the holes will be difficult to maintain. In addition, the test used the epoxy resin to simulate the concrete layer, which shows a high plastic deformation ability, so that the holes can maintain their integrity after a certain amount of lateral deformation. The concrete used in the actual engineering is composed of cement, sand, and stones in a certain mix ratio, and the plastic deformation ability is poor. Therefore, the deformation of the tunnel often leads to the concrete layer cracking and flaking off. This means that the development of shotcrete materials with high strength and high plastic deformation ability is considered to be beneficial in order to maintain the integrity of the tunnels with large deformation or dynamic disasters such as high ground stress, deep, soft rock, and rock burst.

The more severely damaged parts of the holes are located on both sides of the hole, irrespective of specimens with a bedding angle of 0° or 90°, which is the result of the compressive stress concentration areas formed on both sides of the hole under the action of the vertical load. For the plane elasticity problems, the stress distribution around the hole can be expressed by using Kirsch's analytical solution as follows:

where is the radial stress at any point around the hole, is the tangential stress at any point around the hole, is the shear stress at any point around the hole, is the vertical stress, is the horizontal stress coefficient, is the radius of the hole, is the radial distance between the calculated point and the center of the hole, and is the angle between the line between the calculation point and the center point of the hole and the horizontal direction.

The lateral and vertical stress distributions along the hole are shown in Figure 4. In the uniaxial compression test, , and when and on both sides of the hole, then and , thus resulting in a large compressive stress concentration on both sides of the hole. At the top and bottom of the hole, when and , then and , thus, resulting in a tensile stress concentration at the top and bottom of the hole.

3.3 CT scan and the meso-analysis of the cracks of the specimens

The application of the CT technology in rock mechanics is primarily used to analyze the internal structure of rock specimens and the development process of the internal cracks during the laboratory experiments.[33-36] The tests performed CT scanning on the damaged specimens in order to analyze the distribution law of the internal cracks. Due to a large number of specimens, the more typical P1–2 specimen is considered as an example for illustration.

The CT cross-sectional image of the specimen is shown in Figure 5. The CT scan was performed from the front view direction to the rearview direction of the specimen. In the figure, a total of 17 CT scan sections are listed in sequence and marked with the corresponding serial numbers. In Figure 5(1), tensile cracks b and d started from the tensile stress concentration areas at the top and bottom of the holes, and shear cracks a, c, and e started from the collapse of the hole walls on both sides of the holes. As the cracks a and c extended to the depth of the specimen, the secondary cracks f and g were derived from the bifurcation (Figure 5(2)). The bolts can change the stress state of the surrounding rock of the anchored body and improve the mechanical parameters of the surrounding rock, which thus forms an anchoring area within a certain range of the anchored body. The anchoring area shows the effects of weakening, shearing, and arresting cracks. During the development of the cracks, when they approach the anchoring areas of the bolts (Figure 5(3) and (4)), they were weakened (crack b in Figure 5(5), (6), and (7)), arrested (after Figure 5(3) and (4), cracks c and g disappeared), or have changed their propagation paths (crack a in Figure 5(2) turned into cracks a1 and a2 in Figure 5(5)). The specimen contains a total of three rows of bolts (steel pipes). The weakening and arresting effects of the bolts on cracks are reflected in the anchoring areas of the three rows of bolts. In Figure 5(7), tensile cracks b and d were weakened and then disappeared (Figure 5(10)) after the second row of bolts (Figure 5(8) and (9)). In Figure 5(12), cracks e1 and j were weakened and then disappeared (Figure 5(15)) after the third row of bolts (Figure 5(13) and (14)), and the cracks ahi was weakened and changed its propagation path. This means that if the bolts can be reasonably arranged in the engineering rock mass and the closely arranged anchoring areas can be formed in the key rock mass, the development of penetrating cracks can be effectively restrained.

The anchoring zone can restrain the propagation of cracks, but cannot prevent the generation of new cracks (cracks h and i in Figure 5(5)). The new cracks h and i crossed and gathered during the forward propagation process (Figure 5(6)) and merged into crack hi (Figure 5(7)). After the second row of bolts (Figure 5(8) and (9)), the crack disappeared. Cracks a1 and hi gradually changed their propagation paths (Figure 5(10) and (11)) and crossed and merged into through-crack ahi (Figure 5(12)), and at the same time, a secondary crack j appeared in the nearby area. After the third row of bolts (Figure 5(13) and (14)), the secondary crack j disappeared, a new crack k appeared, and the shear crack e1 and the through-crack ahi were weakened (Figure 5(15)). After being far away from the anchoring area, cracks ahi, k, and e1 gradually deepened and expanded to form damage areas (the dark blue area near the hole in Figure 5(17)).

The above crack distribution law shows that the initiation and propagation of cracks in the rock with holes and anchors are not only affected by the stress state of the surrounding rock around the holes, but also underwent the processes of crack weakening, merging, disappearing, and regeneration of the new cracks under the action of bolts. This changing process of cracks is reflected in the stress–strain curve of the rock containing holes and anchors, which is called the fluctuation phenomenon as described below.

3.4 Stress–strain curve

The stress–strain curves of the anchored rock with holes obtained by the test are shown in Table 3. As can be seen from Table 3, since the specimens are made of similar materials and show good homogeneity, the variation regularity of the stress–strain curve of each group of specimens is found to be relatively consistent. The support method and the bedding angle of the specimen with holes and anchors show an influence on the laws of variation in the stress–strain curves. The specific laws are described as follows.

The support structure can improve the uniaxial compressive strength of the specimens, but different support structures can improve the strength of the specimens in different degrees, and the uniaxial compressive strength of the specimens with different bedding angles under the same supporting conditions is also found to be different. The distribution laws of the uniaxial compressive strength of the specimens under different supporting conditions are shown in Figure 6. When the bedding angle is 0deg, the average uniaxial compressive strength of the unsupported specimens is calculated as 4.01 MPa, the average uniaxial compressive strength of the specimens under the systematic rock bolts is measured as 7.13 MPa, and the strength value is increased by 77.80%. It can be seen that the application of systematic rock bolts exhibits a significant effect on the strength of the specimens. The average uniaxial compressive strength of the specimens under the support of systematic rock bolts and concrete and the support of systematic rock bolts, concrete, and steel arches are found to be 7.28 MPa and 7.68 MPa, respectively. As compared to the support of systematic rock bolts, the strength values of the specimens are increased by 2.13% and 7.71%, respectively, which indicates that shotcrete and steel arches are not considered as effective as systematic rock bolts in improving the strength of the surrounding rock.

The average uniaxial compressive strength values of the specimens under the support of steel pipes, the support of steel pipes and concrete, and the support of steel pipes, concrete, and steel arches are calculated as 6.76 MPa, 6.96 MPa, and 7.33 MPa, respectively, and the strength of the specimens under the support of steel pipes is found to be increased by 68.61%, which indicates that the steel pipes show a significant effect on the strength of the surrounding rock, but they are not as effective as the systematic rock bolts. As compared to the support of steel pipes, the strength values of the specimens under the support of steel pipes and concrete and the support of steel pipes, concrete, and steel arches are increased by 2.87% and 8.40%, respectively, which indicates that shotcrete and steel arches are not as effective as steel pipes in improving the strength of the surrounding rock. When the bedding angle is 90deg, the strength enhancement of the support structures on the specimens shows an effect similar to that for the specimens with a bedding angle of 0deg, and the strength enhancement of the specimens is briefly described as follows. The average uniaxial compressive strength of the unsupported specimens is 2.71 MPa, and the average uniaxial compressive strength values of the specimens under the support of systematic rock bolts, the support of systematic rock bolts and concrete, and the support of systematic rock bolts, concrete, and steel arches are calculated as 5.38 MPa, 5.62 MPa, and 5.89 MPa, respectively. As compared to the unsupported specimens, the uniaxial compressive strength values are found to be increased by 98.55%, 107.55%, and 117.47%, respectively. The average uniaxial compressive strength values of the specimens under the support of steel pipes, the support of steel pipes and concrete, and the support of steel pipes, concrete, and steel arches are calculated as 5.14 MPa, 5.36 MPa, and 5.80 MPa, respectively. As compared to the unsupported specimens, the uniaxial compressive strength values are found to be increased by 89.87%, 97.92%, and 114.38%, respectively. It can be seen that the strength enhancement of the support of systematic rock bolts and the support of steel pipes for the specimens with a bedding angle of 90deg is greater than that for the specimens with a bedding angle of 0deg, which indicates that the support structures show a better effect on improving the strength of the surrounding rock of the specimens with a bedding angle of 90deg than the specimens with a bedding angle of 0deg.

The stress–strain curves of the specimens with holes and anchors depend on the bedding angles. The bedding direction of the specimens with a bedding angle of 0deg is observed to be perpendicular to the loading direction. The bedding cracks are compacted and closed under the load, and the initial compaction stage is found to be longer than that of the specimens with a bedding angle of 90deg. However, the bedding of the specimens with a bedding angle of 90deg is fractured and opened under the load, and a small stress drop is observed in the initial stage of loading.

The stress–strain curves of the specimens with holes are different for different support structures. Regardless of whether the specimens with holes contain support structures or not, different degrees of stress drop are observed before and after the peak value of the stress–strain curve. These kinds of variations in stress drop of the specimens with holes indicate the appearance of crack initiation and crack propagation along the hole or the bedding. The stress drop phenomenon of the unsupported specimens mainly occurs before the peak, which is primarily the result of the collapse on both sides of the specimen holes. However, due to the low degree of the stress drop, this local phenomenon cannot be visually observed by the full stress–strain curve.

Under the support of bolts (systematic rock bolts or steel pipes), an obvious fluctuation is observed before and after the stress peak point of the specimens, which is not only related to the collapse of both sides of the holes but also the occurrence of local cracks and post-peak plastic reinforcement caused by the anchoring effect of the bolts. Under the support of bolts and concrete and the support of bolts, concrete and steel arches, due to the supporting effect of concrete and steel arches on the surrounding rock, the hole wall collapse is no longer evident, and the concrete layer is compressed and deformed (bolts and concrete; Figure 7(a)) or there is no longer hole wall collapse (bolts, concrete and steel arches; Figure 7(b)). Therefore, the stress–strain fluctuation of the specimens under these two support conditions is no longer the result of the hole wall collapse, but it is caused by the occurrence and development of cracks and the re-initiation of cracks at the plastic reinforcement stage under the action of the support structures after the stress peak. By comparing the stress–strain curves of the specimens under three kinds of support conditions of bolts, bolts and concrete, and bolt, concrete and steel arches, it is observed that the length of the plastic reinforcement stage of the specimens under the three supporting conditions increases sequentially, and the fluctuation phenomenon of the stress–strain curves becomes more and more evident, which also explains that the fluctuation of the stress–strain curves is closely related to the plastic reinforcement effect of the supporting specimens on the surrounding rock.

4 NUMERICAL SIMULATIONS

In the support mode S4 (shotcrete and systematic rock bolts), two kinds of specimens were simulated by

3DEC. Displacement constraints are applied at the bottom and around the model, and the loading rate at the top of the model is calculated as 1 x 10^{-3} mm/step.

The 3DEC simulation results are compared with the stress–strain curves obtained by the laboratory experiments, as shown in Figure 8, and the numerical simulation and the experimental results are found to be in good agreement. The stress–strain curve of the specimens with a bedding angle of 0deg shows different degrees of fluctuation at the post-peak stage, and the stress falls rapidly after the specimens with a bedding angle of 90deg reach their peak strength values, which is caused by the failure process and the failure mode of the specimens. The specimens with a bedding angle of 0deg primarily show the shear failure controlled by rock materials. The existence of the bedding surfaces causes the specimens to produce secondary cracks along the bedding surfaces or at a certain angle to the bedding surfaces, and the occurrence of secondary cracks causes the stress–strain curves to fluctuate. The failure of the specimens with a bedding angle of 90deg is primarily controlled by the bedding surfaces, which indicates the tension failure along the bedding surfaces. When the load level reaches the peak strength of the specimen, the specimen rapidly deforms along the bedding surface.

The numerical simulation failure mode of 3DEC is shown in Figure 9. The simulation results show the influence of bedding on the failure mode. That is, in addition to the single inclined plane shear failure of the specimens with a bedding angle of 0deg (Figure 9(a)), more failure areas are observed along the bedding surfaces. The failure of the specimens with a bedding angle of 90deg is primarily controlled by the bedding surfaces, and the failure areas are distributed along the vertical bedding. The 3DEC simulated the failure of the specimens along the bedding or joint surfaces, such as slippage and cracks, and visually showed the deformation of the specimens along the bedding or joint surfaces (such as the cracks along the virtual joint and the bedding as shown in Figure 9(a) and (b)).

As shown in Figure 10, the deformation of holes and shotcrete obtained by the 3DEC simulation is quite similar to the results obtained in laboratory tests.

The 3DEC was used to further simulate the triaxial tests of the two specimens under the above support modes in order to observe the damage and fracture of the specimens with holes and anchors and to determine the behavioral characteristics of the support structures. Displacement constraints were applied at the bottom of the model, the confining pressures applied in the X and Y directions were MPa and MPa, respectively, and the loading rate at the top of the model was 1 x 10^{-3} mm/step.

The numerical simulation tests have obtained the evolution process of the damage and fracture of the specimens with bedding angles of 0deg and 90deg under the stress-damage coupling, as shown in Figure 11. The cracks of the specimen with a bedding angle of 0deg started from the top and bottom of the hole, mainly for tensile failure, and then the shear failure occurred on both sides of the hole. Then, the tensile failure areas at the top and bottom of the hole and the shear failure areas on both sides of the hole extended to the inside of the specimen along the horizontal bedding direction, which thus formed a failure area of a certain depth around the hole. The failure process of the simulated specimen with a bedding angle of 90deg is different from that of the specimen with a bedding angle of 0deg. The specimen cracked due to the shear failure of the two sides of the specimen. Thereafter, the cracks developed along the shear failure on both sides of the specimen to the deep part of the specimen; when the cracks developed to the vertical bedding surface, the failure type turned to a mixed vertical shear and split failure along the bedding surface. However, due to the influence of the confining pressure, the specimen did not form a through-crack along the bedding surface, but a shear failure occurred, which shows that the existence of the bedding surface can affect the failure process of the rock mass and the distribution of secondary cracks under triaxial compression, but it cannot affect the final failure mode.

5 THE ANCHORING MECHANISM OF THE SUPPORT STRUCTURE ON THE SPECIMEN

The support structures show a significant influence on the strength characteristics, deformation characteristics, and the laws of the crack propagation of the specimens. The stress distribution around the holes without the support structures can be solved by formulas (1)–(3). The mechanical model of the anchoring hole with the anchoring effect of bolts is shown in Figure 12.

According to the literature [37], the analytical solution of the stress in the anchored zone and the non-anchored zone can be obtained as follows:

The radial stress in the anchored area is determined by

The tangential stress is calculated as The radial displacement is obtained by where Its first derivative is given by

The radial stress in the non-anchored zone is determined by

The tangential stress is calculated as The radial displacement is obtained by The radial stress at the interface between the anchored zone and the non-anchored zone is measured as follows:

The internal support pressure of the hole is shown in Equations (4)–(12). For other symbolic meanings and solutions, refer to the literature. [37]

Therefore, the support of bolts changes the stress and displacement response of the surrounding rock. In addition, some scholars have observed that bolts can effectively improve the mechanical parameters of the rock mass and increase the peak strength and the residual strength of the rock mass, thus reduce the range of the plastic zone of the surrounding rock mass of the tunnel and the displacement of the tunnel surface and maintain the stability of the surrounding rock,[38,39] which is found to be consistent with the test results obtained in this paper.

The concrete and steel arches induce internal support pressure on the tunnel, which is related to the material and support parameters of the concrete and steel arches. In calculations, the concrete and steel arches are often considered as a one-layer support structure, and the supporting stiffness [40] is evaluated as follows:

where and are the concrete elastic modulus and Poisson's ratio, is the thickness of the layer of concrete and steel arches, and is the tunnel radius. The support pressure inside the tunnel is obtained as follows:

where is the hole wall displacement. The tangential stress of the concrete layer is evaluated as follows:

When the tangential stress exceeds the ultimate strength value of the concrete layer, the cracks occur in the concrete layer and gradually develop and the peeling and flaking off of the concrete layer also occur. By substituting formula (14) into formulas (4)–(12), the mechanical response of the tunnel on the surrounding rock under the support of bolts, concrete and steel arches can be obtained.

6 DISCUSSION

In this paper, the laboratory experimental method is used to obtain the mechanical properties and the deformation characteristics of the rock with holes and anchors, and to obtain the supporting mechanism of the support structures on the holes and the surrounding rock. However, there are several crucial factors that require further explanation and discussion.

The specimens are made of similar materials with good homogeneity, and the dispersion of the test data is small. There are still several factors that require adequate attention during the tests. The first factor is the distribution of the bolts. During the arrangement process, the bolts should be distributed as evenly as possible. However, in the process of arranging the specimens layer by layer, the bolts can easily deviate, the ideal state is that when the five bolts, shown in Figure 6(4), are all on the same level. The second factor is that the epoxy resin with high plastic deformation ability should be used in the tests in order to simulate the shotcrete layer. Therefore, during the tests, no concrete cracking and peeling, and flaking off of the concrete layer on similar engineering sites were observed. After the tests, the specimens were broken, and the simulated concrete components (Figure 10(d)) were taken out carefully, and the plastic deformation of the concrete layer was observed. Although this experimental result is different from that of the actual engineering projects, it is obviously beneficial for maintaining the integrity of the tunnel. The last and important factor is that the loading fracture process of the specimens was not observed by the real-time CT scanning observation. How to prepare smaller-scale specimens with holes and anchors for the real-time observation and study more microscopic dimensions in order to observe and analyze the law of crack evolution is an important question that should be discussed in the next step.

In this paper, the analytical formulas related to the stress and displacement of the surrounding rock in the anchored area and the non-anchored area under the action of supporting components are discussed. Based on the test results, it is concluded that the bolts primarily realize the anchoring effect by changing the stress state of the surrounding rock in the anchoring area and by improving the mechanical parameters of the surrounding rock. The anchoring area demonstrates the functions of weakening, arresting, and changing the propagation path of cracks, which thus improves the bearing capacity of the surrounding rock. It is important to note that the theoretical analytical formula is obtained under ideal and simplified conditions, which can qualitatively well explain the action mechanism of support structures on the stress state of the surrounding rock, but the calculation and test results can show a certain deviation if the theoretical analytical formula is used to quantitatively calculate the stress displacement. For example, the calculation in the process of the installation of bolts is based on the assumption that the bolts are evenly arranged on the same plane. The installation quality of bolts in the actual engineering projects (including the laboratory tests in this article) is significantly affected by human factors. It is often difficult to maintain the installation angle of the bolts and the grouting quality, which thus affects the anchoring effect of the bolts.

7 CONCLUSIONS

In this paper, similar simulation materials are used for prefabricating specimens with holes and anchors, and laboratory uniaxial compression tests are carried out. The strength, deformation characteristics, and the laws of crack propagation are studied by using the CT scan, and the coupled stress-damage simulation tests are carried out by using the 3DEC numerical simulation method. The damage evolution process of the specimens with bedding and holes under the action of support structures is discussed.

The support structures can improve the uniaxial compressive strength of the specimens, but different support structures exhibit different degrees of supporting effects on the strength of the specimens. The bolts can significantly improve the strength of the specimens, but the supporting effects of concrete and steel arches are not evident. With different bedding angles, the support structures also show different strength enhancement effects on the specimens. The support structures demonstrate a better effect on improving the strength of the surrounding rock of the specimens with a bedding angle of 90deg than the specimens with a bedding angle of 0deg.

Concrete and steel arches can induce support pressure on the tunnels, effectively prevent the holes from peeling, spalling off and other damages and help maintain the integrity of the holes. The existence of bedding surfaces can affect the failure process of the rock mass and the distribution of the secondary cracks, but it cannot affect the final failure mode.

The analytical formulas related to the stress and the displacement of the surrounding rock in the anchored area and the non-anchored area under the action of supporting structures are discussed herein. Based on the test results, it is concluded that the bolts primarily realize the anchoring effect by changing the stress state of the surrounding rock in the anchoring area and by improving the mechanical parameters of the surrounding rock. The anchoring area demonstrates the functions of weakening, arresting, and changing the propagation path of cracks, which thus improves the bearing capacity of the surrounding rock.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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