Research Article

Experimental Study on Load Bearing Characteristics of Steel Fiber Reinforced Concrete Lining in the Soft Surrounding Rock Tunnel

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Tunnels in soft rock with high ground stress will encounter the problem of large deformation of surrounding rock. The study of new high-performance tunnel lining materials is of great significance to improve the safety of tunnel excavation in soft rock with high ground stress. In this paper, the bearing characteristics of the plain concrete, the reinforced concrete, and the steel fiber reinforced concrete lining are studied by the indoor model experiment. By extracting the displacement and stress data of typical parts of lining, the bearing characteristics of the steel fiber reinforced concrete lining are analyzed and summarized. The test results show that the initial crack load and ultimate load of the steel fiber reinforced concrete lining are significantly higher than those of the other two materials, and the crack development path is more tortuous, and the number of cracks is greater. Steel fiber can improve the bearing capacity and deformation capacity of the lining structure so that the failure mode of the lining structure changes from brittle shear failure to ductile bending failure. It is concluded that steel fiber reinforced concrete can improve the toughness of lining. Because of its excellent mechanical properties, steel fiber reinforced concrete can completely replace the conventional reinforced concrete as a new lining material for soft rock tunnel. The above research results are of great significance to the design and construction of tunnel lining in the soft surrounding rock.

1. Introduction

Under the condition of the soft surrounding rock, it is required to close the rock face as soon as possible after tunnel excavation, and the tunnel lining shall be able to adapt to deformations and provide sufficient support force. The previous studies have shown that the lining under a soft surrounding rock will develop surface cracks after long-term creep [1, 2]. Although slight cracks on lining surfaces will not directly lead to a reduction of bearing capacity because of the horseshoe shape cross section of tunnel lining, they are inducements of more serious disasters, meanwhile reducing stability and durability of lining structure indeed [3]. Fiber reinforced concrete is a kind of convenient building material with excellent mechanical properties. At present, the research on fiber reinforced concrete as an alternative to ordinary tunnel initial support (steel mesh + shotcrete) has been carried out [4].

In addition, since the long-term creep deformation characteristics of soft surrounding rock will lead to large deformation disasters, it is very important to maintain the structural integrity of soft rock tunnel lining in a cracked state [5]. Caratelli et al. [6] proposed that fiber shotcrete can replace traditional reinforced concrete as a tunnel lining material, mainly because the existence of fiber improves the deformation capacity of lining and controls the opening degree of lining cracks. The compression, tensile, and flexural strength of concrete are very important for the role of the tunnel lining structure, and the tensile strength plays a leading role in crack control [7]. Yoo et al. [8] found that the tensile stress of plain concrete structure decreases immediately after cracking, but after adding a certain volume of fiber, the fiber can still maintain a certain bearing capacity, thus avoiding the sudden failure of composite materials when structural cracks occur. Since most of the soft rock tunnels are accompanied by developed groundwater, the
performance of lining seepage prevention is also very important. The researchers found that the higher the fiber content and the shorter the fiber length, the more obvious the plastic crack resistance and antiseepage effect of concrete [9, 10].

Furthermore, among various kinds of fiber reinforced concrete, steel fiber reinforced concrete has greater performance advantages [11]. The researchers have found that steel fiber reinforced concrete can also maintain the integrity of the structure in the cracking state by strengthening the tensile strength of concrete [12], and the bridging effect of steel fiber can significantly reduce the crack width of tunnel lining [13]. The improvement of lining performance after the application of steel fiber is not only to improve the tensile, flexural, shear, and toughness of concrete but also to have better crack distribution characteristics [14], especially to delay and control the crack width and expansion of concrete [15]. According to the full-scale test, Gong et al. [16] proposed that the structural performance of steel fiber reinforced concrete is completely better than that of reinforced shotcrete, which has a higher initial cracking load and energy absorption capacity at initial cracking. In addition, the researchers found that the wear resistance, corrosion resistance, and seismic performance of steel fiber reinforced concrete lining, especially fine fiber, are better than those of conventional reinforced shotcrete under the same high damage state [17, 18]. Therefore, considering the construction characteristics, mechanical properties, and deformation ability of the initial support of soft rock tunnels, steel fiber reinforced concrete is a perfect lining material for soft rock tunnel in theory.

In recent years, the research on steel fiber reinforced concrete lining is mainly focused on the application of shallow buried tunnel or tunnel with mild geological conditions, but there is a lack of research on steel fiber concrete lining of soft rock tunnels in areas with high ground stress under extreme geological conditions. In order to explore the advantages of steel fiber reinforced concrete as lining material of high in situ stress soft rock tunnels, so as to improve the safety of tunnel excavation in high in situ soft rock. In this paper, taking V-grade surrounding rock section of sericite phyllite in Yangjiashan Tunnel of Guangzhou Gansu Expressway as the research object, the bearing characteristics and antideformation capacity of steel fiber concrete lining under soft rock conditions are studied through a similar test. The results of this paper are of great significance to improve the support control system of a large deformation tunnel in soft rock.

2. Engineering Background

Part of the tunnel body of Yangjiashan Tunnel passes through Silurian sericite phyllite section, with V-class surrounding rock. The rock mass is epiblastic nature and phyllite structure, which is relatively broken. The compression strength is only 5–6.5 MPa.

Sericite phyllite is weak in lithology and prone to dislocation. When the rock mass encounters water, it is very easy to soften and deform, which further worsens the stability of surrounding rock, as shown in Figure 1. Under the action of high ground stress, the surrounding rock of the tunnel will deform rapidly and the stress of the supporting structure will increase sharply, which will lead to the failure of the tunnel support structure due to instability, which will seriously affect the safety of the tunnel construction and operation.

The Yangjiashan Tunnel is a horseshoe-shaped section (five-hearted circle) with a span of 12.54 m and a height of 9.79 m. The structure design of the sericite phyllite V-class surrounding rock section: the initial support is I18 steel frame @80 + φ8 steel mesh + anchoring agent and φ22 bolt + 30 cm thick C25 shotcrete; the second lining is 40 cm thick C25 steel reinforced concrete. It is proposed to replace the original design (φ8 steel mesh + 30 cm thick C25 shotcrete) with the 30 cm thick CF25 steel fiber reinforced concrete.

3. Experimental Procedure

3.1. Similar Parameter Design. When the geometric similarity ratio is less than 50, the rock-soil model test results can be in good agreement with the actual engineering effect. The test is carried out in a vertical steel plate model test bench with a size of 4.3 m length × 3.7 m width × 0.5 m thickness, and the tunnel model axis is consistent with the thickness direction of the test bench. In order to eliminate the boundary effect of the test bench as much as possible, the length of the test bench should be greater than 6 times the tunnel span, so the geometric similarity ratio is taken as 20.

In the study by Wang et al. [19], the elastic modulus of CF25 steel fiber reinforced concrete is 2.5–3.15 × 10⁵ MPa in the actual project. The initial support of the model is proposed to be simulated by the gypsum mixed material, and the elastic modulus of the gypsum mixture is 1.05–1.7 × 10⁵ MPa [19], so the elastic modulus similarity ratio is taken as 20.

The similarity ratio of other parameters is derived according to the similarity criterion [20], as shown in Table 1.

3.2. Test Equipment and Materials. The vertical steel plate model test bench is shown in Figure 2, and the tunnel lining model is shown in Figure 3, with a thickness of 1.5 cm. The measuring instruments include pressure box (DYB-1 micropressure sensor, as shown in Figure 4(a)), displacement meter (YHD displacement sensor, as shown in Figure 4(b)), and static strain collector.

The similar materials of the surrounding rock are made of barite powder, machine oil, river sand, quartz sand, and rosin in a certain proportion. The physical and mechanical parameters of surrounding rock are determined by material property test [21], as shown in Table 2.

In this test, the strength grade of the reinforced concrete is C25, the water cement ratio is 0.686, and the steel mesh is simulated with a double-layer finished steel wire mesh with a diameter of 0.5 mm (the general φ 0.5 steel wire can simulate...
φ10 steel bars, considering that the actual project is a steel skeleton, so this paper uses φ 0.5 steel wire to simulate φ8 steel mesh), as shown in Figure 5.

The strength grade of the steel fiber reinforced concrete is CF25, and the water cement ratio is 0.588. The special test steel fiber (water-soluble Dramix steel fiber) is used to simulate the actual steel fiber, as shown in Figure 6, and a proper amount of white emulsion glue is added to improve the bonding force between the steel fiber and the gypsum.

The physical and mechanical parameters of reinforced concrete and steel fiber concrete lining are determined by the experimental research of standard test pieces [22, 23], as shown in Table 3.

3.3. Test Grouping and Layout of Measuring Points. The test is divided into three groups: plain concrete lining, reinforced concrete lining, and steel fiber reinforced concrete lining. Each group has three specimens. The steel fiber content is determined to be 42 kg/m³ according to the bending toughness test.

In order to study the bearing characteristic of the steel fiber reinforced concrete lining, and considering that the lining specimen is symmetrical structure and bears the symmetrical load, the measuring points are set in the typical positions (vault, left haunch, middle of the left side wall and inverted arch) where the surrounding rock contacts the lining structure. The arrangement of measuring points is shown in Figure 7.

3.4. Test Procedure. First, fill the soil to the bottom of the lining invert arch, and tamp it every 20 cm, and simulation of the density of surrounding rock material can be accurately achieved by controlling the number of tamping times. Then, the lining model is embedded; the DYB-1 micropressure sensor and YHD displacement meter are arranged at the same time.

Fill the soil to the specified height of the surface (tamping of the part above the inverted arch, fill the space in the lining with rags, reduce the compaction intensity, increase the compaction times, and then compact to the predetermined graduation line for the next compaction).

According to the buried depth of the tunnel and the gravity of surrounding rock, the designed load is estimated to be 2 T/grade. Then through the hydraulic device, the designed load is placed on the Jack, and the load is evenly transmitted to the surrounding rock through the reaction device and load distribution beam. The lateral large stiffness plate of the test bench is used to transfer the passive Earth pressure.

Taking the crack through the lining as a sign, the loading process is gradual until the lining structure is damaged. When the lining structure is damaged, the loading process stops and the test ends.

4. Test Results and Data Analysis

4.1. Failure Process. The failure law of the lining structure under the action of the load was approximately the same. First, the first longitudinal crack appeared on the inner side of the vault or the middle of the inverting arch (the initial crack load of plain concrete lining and reinforced
Figure 4: Test sensors. (a) DYB-1 micropressure sensor. (b) YHD displacement sensor.

Table 2: Physical and mechanical parameters of surrounding rock.

| Material                        | $E$ (MPa) | $\mu$ | $\gamma$ (kN·m$^{-3}$) | $c$ (kPa) | $\phi$ (°) |
|---------------------------------|-----------|-------|------------------------|-----------|------------|
| Original surrounding rock       | 1210      | 0.41  | 18                     | 120       | 23         |
| Similar materials of surrounding rock | 58.4     | 0.43  | 18.7                   | 5.7       | 25         |

Figure 5: Double-wire mesh.

Figure 6: Steel fiber. (a) Engineering steel fiber. (b) Test steel fiber.
concreteliningwereboth10t,whiletheinitialcrackload
of steel fiber concrete lining was 12 t). With the increase
ofthe load, the crack width increased and continued to
expand to the outside of the lining. Then, some small
longitudinal cracks appeared in the middle or foot of the
side wall of the lining, and the width and depth of the
cracks increased with the increase of load. Finally, the
longitudinal crack in the vault or the middle of the
inverting arch penetrated the whole structure, and the
lining structure was completely damaged.

Although the failure law of the lining structure is similar,
the development process and the final state of structural
failure of the steel fiber reinforced concrete lining, the
reinforced concrete lining, and the plain concrete lining are
quite different. The differences are as follows.

4.1.1. Plain Concrete Lining. The first longitudinal crack of
the plain concrete lining appeared in the inner side of the
vault. With the increase of the load, the longitudinal crack
appeared in the middle of the inverted arch and the left and
right side wall feet, and the width and depth of the crack
expanded rapidly. Finally, the first crack at the inner side of
the vault penetrated the whole structure, and the lining
structure was completely damaged. So far, the number of
cracks in the lining structure was 4. The cracking condition
of the plain concrete lining is shown in Figures 8 and 9.

4.1.2. Reinforced Concrete Lining. The reinforced concrete
lining appeared at the first longitudinal crack in the middle
of the inner side of the inverted arch. With the increase
of the load, longitudinal cracks appear in the vault and the
wall footings, and the width and depth of the cracks
gradually increase. As the load continued to increase,
longitudinal cracks began to appear in the haunch and
inverted arch, and the number of cracks was 9 when the
lining structure was destroyed. Because of the restraining
effect of the steel mesh, the development path of cracks is
more tortuous than that of the plain concrete lining, which
delays the damage of the lining structure. The cracking
condition of the plain concrete lining is shown in Fig-
ures 10 and 11.

4.1.3. Steel Fiber Reinforced Concrete Lining. The steel fiber
reinforced concrete lining first appeared a very small lon-
gitudinal crack in the vault. With the increase of load, the
depth of the crack increased slowly due to the restraint of the
steel fiber, and the path of the crack development also be-
came tortuous and delayed the damage of the structure.
When the depth of the crack reached 80% of the section
height, the depth of the crack changes little, and the width
increased continuously. As the load continues to increase,
the cracks gradually appeared in the inverted arch, vault, side
wall, and other parts. Further increasing the load, the lon-
gitudinal cracks appeared in other parts of the structure
gradually. At last, the number of cracks was up to 12, and no
penetrating crack appeared in the structure. The cracking
condition of the steel fiber reinforced concrete lining is
shown in Figures 12 and 13.

Due to the contribution of the steel fiber to the crack
resistance of the structure. The initial crack load of the steel
fiber reinforced concrete lining is higher than that of the
former two kinds of the lining (increase about 20%).
Figure 8: Lining cracks of the plain concrete. (a) The first crack (vault). (b) The second crack (inverted arch). (c) The third crack (left side wall feet).

Figure 9: Distribution of lining cracks of the plain concrete.

Figure 10: Lining cracks of the reinforced concrete. (a) The first crack (inverted arch), (b) The third crack (left side wall feet).

Figure 11: Distribution of lining cracks of the reinforced concrete.
4.2. Contact Pressure. Extract the contact pressure of each measuring point (surrounding rock and lining) and draw the relationship curve between contact pressure and load, as shown in Figure 14.

It can be seen from Figure 14 that the actual Earth pressure acting on the lining structure is smaller than the theoretical calculation value (about 60%–70% of the theoretical value of the load structure model), and the load is shared by the surrounding rock and the lining structure together. The theoretical value of the load structure model is the sum of soil gravity and loading force.

The contact pressure increases with the increase of the load. When the load reaches the initial crack load, the cracks appear in the vault or inverted arch of the lining structure, and the growth rate of the contact pressure slows down. As the steel fiber reinforced concrete has better crack resistance and deformation control ability, and the stress distribution of the whole lining structure is more uniform. After the first crack appears in the lining, it still can bear the load up to 2 times of the initial crack load without penetrating crack.

In Figure 14(c), the contact pressure in the middle of the side wall of the plain concrete lining and the reinforced concrete lining increases sharply at the load of 12 t and 14 t, respectively. At this time, the lining structure shows the initial crack, the section high-span ratio suddenly decreases, and the side wall is squeezed into the direction of the surrounding rock rapidly, causing the contact pressure here to increase sharply. The bearing capacity of the lining structure is generally controlled by compression and bending. That is, under the action of compression and
bending load, the concrete in the tension zone cracks due to the bending tensile stress reaching the ultimate tensile strength. Due to the insufficient toughness of the plain concrete and reinforced concrete, plain concrete lining and reinforced concrete lining have brittle failure characteristics at typical positions, which will be destroyed immediately when cracks occur.

4.3. Radial Displacement. Extract the radial displacement of each measuring point and draw the relationship curve between radial displacement and load, as shown in Figure 15.

It can be seen from Figure 15 that the radial displacement of the lining structure increases with the increase of load. Before the initial crack load, the radial displacement of each measuring point is basically linear with the load. After the initial crack load, the radial displacement growth rate of the lining structure increases obviously, the plain concrete is larger than the reinforced concrete, and the reinforced concrete is larger than the steel fiber concrete. This shows that the crack will lead to the increase of deformation rate of the lining structure, and the steel fiber reinforced concrete lining structure has the most obvious inhibition effect on the increasing trend of the deformation rate.

Under the same load, the radial displacement of the plain concrete is larger than that of the reinforced concrete, and the reinforced concrete is larger than that of the steel fiber concrete. Taking the vault measuring point as an example (Figure 15(a)). When the load reaches 16 t, the radial displacement of the plain concrete is 23 mm, that of the reinforced concrete is 15 mm, and that of the steel fiber reinforced concrete is 11 mm. The results show that the toughness, crack resistance, and deformation control ability of the steel fiber reinforced concrete lining are better than those of the reinforced concrete and the plain concrete lining.

4.4. Load Bearing Characteristics. Extract the contact pressure and radial displacement of each measuring point during the loading process and draw the load bearing characteristics curve of lining structure, as shown in Figure 16.
It can be seen from Figure 16 that during the loading process, the measuring points at the vault, the haunch, and the middle of the inverted arch are constantly deforming in the direction of the tunnel, and the bearing characteristic curves of the three measuring points are consistent. However, the measuring point in the middle of the side wall continuously deforms toward the surrounding rock, and its bearing characteristic curve is different from the other three measuring points. Therefore, the following takes the measuring points of the vault and the middle of the side wall as examples to analyze the bearing characteristics of the lining structure of various materials.

4.4.1. Vault. After the initial crack load of the plain concrete and the reinforced concrete lining is reached, the radial displacement increasing rate of the measuring points increases abruptly, and the failure mode of the lining structure is a brittle shear failure. The plain concrete quickly reaches its ultimate load (almost the same as that of the initial crack load), and the ultimate load of the reinforced concrete is about 50% higher than that of the initial crack load.

When the steel fiber reinforced concrete lining reaches the initial crack load, the increasing rate of radial displacement of the measuring point is relatively slow, and the structure still has a high bearing capacity. When it bears twice the initial crack load, the structure still has no penetrating crack. This shows that the steel fiber can improve the bearing capacity and deformation capacity of the lining structure, and the failure mode of the lining structure is a ductile failure.

4.4.2. Middle of Side Wall. In the process of loading, the side wall of the lining deforms towards the surrounding rock. In the process of deformation, the contact pressure acting on the lining structure is increasing because of the constraints of the surrounding rock.

After reaching the initial crack load, the deformation of the steel fiber reinforced concrete under the same
surrounding rock pressure is significantly reduced. Due to the good crack resistance of the steel fiber, the steel fiber reinforced concrete lining can still bear a large bending moment after the initial crack load, so the steel fiber reinforced concrete lining has great potential to resist deformation. Combined with the analysis of the bearing characteristic curves of other measuring points, it can be seen that the bearing capacity and deformation capacity of each part of the lining structure can be significantly improved by adding steel fiber. Because the ability of the lining structure to resist cracking and crack propagation is significantly improved, and the toughness of the lining structure is improved. After adding steel fiber, the failure mode of lining structure changes from the brittle shear failure to the ductile failure, even the ductile bending failure.

Under the action of compression and bending load, the tensile zone of fiber concrete lining will crack, and the lining can continue to bear load after cracking. Due to the existence of the steel fiber, the cracked section can still transfer axial force, shear force, and certain bending moment. With the increase of deformation, structural stability becomes worse. At this time, the cracking part of the lining is equivalent to forming a plastic hinge, as shown in Figure 17(a). The tensile stress transferred by the fiber in the cracking lining section will decrease with the increase of crack width, and its tensile stress distribution is shown in Figure 17(b), and $f_c$ in the figure is the compression strength of fiber reinforced concrete. The stress-strain curve of the compression zone of the steel fiber reinforced concrete is the same as that of ordinary concrete.

Bearing mechanism of the steel fiber reinforced concrete lining structure: under the action of surrounding rock pressure, the lining appears initial crack (the first plastic hinge appears); with the increase of pressure, the plastic hinge will rotate and more plastic hinges will appear; until the lining structure changes from statically indeterminate structure to rotatable structure, the lining structure will be destroyed finally. The experimental results are in good agreement with the results of previous studies.

Figure 16: Bearing characteristic curves of lining structure. (a) Measuring point 1(vault). (b) Measuring point 2(hauch). (c) Measuring point 3(middle of the side wall). (d) Measuring point 4(middle of the inverted arch).
5. Summary and Conclusions

In this paper, the mechanical behavior of the plain concrete, the reinforced concrete, and the steel fiber reinforced concrete lining are studied by means of an indoor model test. By analyzing the stress and displacement data of the measuring points in the typical parts of the lining, the bearing characteristics of the steel fiber reinforced concrete lining are summarized. The main conclusions are as follows:

(1) Due to the insufficient toughness of the plain concrete and the reinforced concrete, and the bearing capacity of the tunnel lining structure is generally controlled by compression and bending, both the plain concrete and the reinforced concrete have the brittle failure characteristic of breaking immediately at the typical part of the lining. The brittle failure characteristics of the material have greatly increased the safety problems of soft rock tunnel lining construction.

(2) Compared with the plain concrete and the reinforced concrete lining, the initial crack load of steel fiber reinforced concrete lining is increased by about 20%, and the ultimate load is increased by more than two times. After the initial crack load, the steel fiber reinforced concrete lining can still bear a larger bending moment. When the structure is damaged, the steel fiber concrete lining will appear cracked in many places. At the same time, the crack development path of the steel fiber reinforced concrete lining is more torturous than that of the plain concrete and the reinforced concrete lining, and the crack depth increases slowly during the loading process. Compared with plain concrete and the reinforced concrete, the steel fiber reinforced concrete has good crack resistance and deformation control ability.

(3) The bearing characteristic curves of the plain concrete lining and the reinforced concrete lining tend to converge rapidly after the initial crack, and the surrounding rock pressure carried by the lining no longer increases as the deformation increases. The bearing characteristic curves of the steel fiber concrete lining still have a rapid upward trend after the initial crack. When the load is increased to twice the initial crack load, the surrounding rock pressure that the steel fiber concrete lining can bear is still increasing. Under the condition of the soft surrounding rock, the steel fiber reinforced concrete lining can coincide with the soft surrounding rock characteristic curve after a certain deformation and finally achieve the stable state of surrounding rock-structure. In conclusion, steel fiber reinforced concrete is a kind of lining material with excellent mechanical properties for soft rock tunnel.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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