Using Energy-Absorbing Dampers to Solve the Problem of Large Deformation in Soft-Rock Tunnels: A Case Study

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Abstract: The commonly used strength design concept of tunnel support structures is inadequate to address the large deformation of soft rock. This study designed a series of energy-absorbing dampers (EDs) with low stiffness and high deformation capacity based on the energy principle. The ED was directly installed on the steel arch, which used its compression deformation to release the surrounding rock pressure and absorb the surrounding rock deformation to ensure the stability of the initial support structure. A compression test analyzed the ED’s mechanical properties, optimizing the structural parameters. The preliminary test results showed that the arc energy-absorbing damper’s (AED-I) peak strength (15.33 Mpa) was lower than the standard compressive strength of C25 shotcrete, with a safety factor of 1.63. The AED-I’s maximum compression ratio was 73.20%. To further improve the AED-I’s reliability and ability to absorb the deformation of surrounding rock, the bending radius of the AED-I’s energy-absorbing steel plate was reduced from 1800 mm to 1300 mm. After optimization, the AED-IO’s peak strength was reduced to 10.5 Mpa, and the safety factor increased to 2.38. The maximum compression ratio of the AED-IO also increased to 75.79%. The AED-IO has been applied to treat the large deformation of soft rock in the Zhongshao Tunnel on the Yuchu Expressway. Compared with a traditional support method, the maximum surrounding rock pressure was only 0.13 Mpa in the section where the AED-IO was applied. The maximum steel arch stress was 122.26 Mpa, far less than its uniaxial compressive strength. The application of the AED-IO ensures the stability of the initial support structure. Meanwhile, using an AED-IO saves CNY 24,323.85 per meter and reduces waste emissions by 20 tons.

Keywords: mountain tunnel; soft rock; large deformation control; energy principle; energy-absorbing dampers

1. Introduction

High in situ stress on soft-rock tunnel supports is an urgent problem in the tunnel construction field [1]. After excavation, under the action of high in situ pressure, the soft surrounding rock experiences large deformation, which persists for a long time [2]. The traditional, rigid-support concept attempts to limit surrounding rock deformation by increasing the stiffness of the initial support structure, for example, using high-stiffness steel arches, spraying high-strength concrete, and using multilayer initial support structures [3,4]. However, such initial supports with high stiffness and low deformation capacity ultimately cannot limit the deformation of the surrounding rock. The rock will still crack, damage, or collapse, resulting in serious construction accidents [5]. Meanwhile, replacing the collapsed initial support structure will cause delays in the construction period, repeated investment in support materials and costs, and excessive amounts of construction waste.

The soft-rock tunnel design has gradually changed from a traditional, rigid-support concept to a flexible one based on the energy principle [6]. Global scholars and engineers have conducted extensive research and achieved rich findings. Wang et al. [7] studied the
applicability of an energy-absorbing support system, comparing the support performance with that of an ordinary rock bolt support under the same simulated geologic conditions. He et al. [8] and Yokota et al. [9] developed an energy-absorbing bolt that can be used to prevent rockburst and large deformation. Chen et al. [10] and Wu et al. [11] evaluated the supporting effect of an energy-absorbing bolt from the angle of mechanical-work-transfer efficiency. The results are significant for optimizing the bolt length and reducing unnecessary material use. Sun et al. [12] proposed an NPR (Negative Poisson’s Ratio) constant resistance and large deformation anchor-cable support system, which they applied in a superlong and high-stress soft-rock tunnel in Gansu, China [13,14].

Meanwhile, as a large country with a great deal of engineering construction and energy consumption, China must integrate sustainability into its engineering construction practices. Relevant data show that China’s energy efficiency is only 33%, lower than the advanced international level. However, the energy consumption of primary products is 40% higher than the advanced international level [15]. Therefore, in recent years, the concept of green and sustainable development has gained increasing popularity in China. To better guide the sustainable construction of basic transportation facilities, the Ministry of Transport of China issued the Green Transportation Standards System in 2016. According to this policy, new public transport facilities must meet sustainable energy conservation, emission reduction, and resource recycling standards [16]. In addition, the Green Transportation Facility Assessment Technical Requirements draft has been released and widely collected for feasible suggestions from the whole society [17]. As an essential part of China’s basic transportation facilities, the entire construction process of tunnels must be integrated with the concept of sustainability. Only through continuous improvement and testing of support structures can the sustainable construction of tunnels be realized. Shahri et al. [18–20] used P-wave velocity and a point-load test to evaluate the uniaxial compressive strength of marl, established a spatial soil-prediction model based on an artificial neural network, and analyzed regional differences. Yu et al. [21] proposed a composite support system to improve the stability and safety of soft-rock tunnels by using orthogonal experiments, numerical simulation, and field observation. Tian et al. [22] obtained a calculation formula for an unsupported span of a shallowly buried tunnel in the soft-rock layer. The research results are of great significance for optimizing the design of tunnel support structures and saving the amount of support materials required [23–25]. Zhang et al. [26] analyzed various factors affecting the large deformation of soft-rock tunnels (i.e., mineral composition, joints and fractures, mechanical properties, etc.). They provided a theoretical basis for deformation control and supported the design of soft-rock tunnels. Zhang et al. [27] used the coupling limit and a reliability-analysis method to study the stability of soft-rock tunnels [28–30]. Zhan et al. [31] analyzed the stability-control theory of soft-rock tunnels using the Nishihara model and a Drucker–Prager modification of the Mohr–Coulomb yield condition.

Although existing relevant research results have opened the way for this study, limitations still exist. The previous studies have a specific effect on controlling the large deformation of soft-rock tunnels, but the problems of complex structure, intricate construction, and high cost remain. This study aims to develop an effective, economical, and sustainable support structure to address the large deformation of soft-rock tunnels. The entire study was carried out under the guidance of the energy principle. A series of energy-absorbing dampers (EDs) were designed in this study, and their mechanical properties were tested and optimized by compression testing. The research results will be applied to engineering practices to control the large deformation of soft-rock tunnels.

2. Methodology
2.1. Energy Principle
2.1.1. Design Method Based on Energy Principle

The previous research results show that a collapsed arch is not the general law of surrounding rock deformation after tunnel excavation. Especially when the arch has been excavated, and there is a support structure to provide support resistance, the surrounding
rock of a deeply buried tunnel will not form a collapsed arch. The supporting structure is subjected to deformation pressure rather than the vertical load of a collapsed arch. The characteristic curve of surrounding rock shows that the deformation pressure will decrease with the increase in surrounding rock deformation.

Under certain conditions of the surrounding rock, the energy released by the tunnel from excavation to stability is constant. Therefore, tunnel support can be designed according to the energy principle. The theoretical formula is as follows:

$$W = F \times S$$

where $W$ is work, a constant and scalar; $F$ is force, a vector; and $S$ is displacement, also a vector.

According to Equation (1), when the work is constant, the combination of force and displacement is infinite. The traditional strength design theory usually increases the support resistance by increasing the thickness and stiffness of the support structure. This design method based on strength theory will cause the support structure to bear large internal force but only produce small displacement. Once the internal force exceeds the peak strength of the support structure, it will become unstable and fail, leading to serious safety accidents and economic losses.

The core of the design method, based on the energy principle, is to reduce the internal force of the support structure by increasing its deformation capacity, maintaining relative stability, and avoiding instability and failure. At the same time, the energy accumulated in the surrounding rock is released. Figure 1 shows the characteristic curves of traditional support and energy-absorbing support.

![Figure 1. Support characteristic curve and surrounding rock characteristic curve: (a) traditional support; (b) energy-absorbing support.](image)

However, commonly used concrete, steel arch, and other support structures are characterized by small deformation and large stiffness. Therefore, it is necessary to improve the traditional support structure to create the characteristics of large deformation and small stiffness to meet the demand of soft-rock tunnel support.

2.1.2. Deformation Pressure

Stress on the initial support structure mainly comes from the deformation pressure of the surrounding rock. The coupling action of the surrounding rock and support structure bears the stress released after tunnel excavation. Under the action of deformation pressure, most support structures in the area of the tunnel’s arch are in a state of small eccentric compression. The stress mode is pressure–shear control, and the failure mode is the shear failure of the oblique section, rather than the tensile failure of the normal section controlled by bending–pulling. Figure 2 shows the soft-rock large deformation status of the Yangshan tunnel on the Menghua Railway; the shear failure occurred in shotcrete, and the buckling failure occurred in the grille steel frame.
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Figure 2. The initial support yielded and was damaged.

Therefore, when facing the support problem of a large-deformation tunnel with soft rock, the reserved deformation amount of the tunnel should be appropriately increased. Meanwhile, the energy-absorbing support structure with greater deformation capacity and less stiffness in the hoop direction should be adopted.

2.2. Energy-Absorbing Damper (ED)

An ED comprises two transverse connecting steel plates and two vertical energy-absorbing steel plates. The two transverse connecting steel plates are placed in parallel, and the two vertical energy-absorbing steel plates are vertically welded onto the connecting steel plates. The ED is connected to the steel arch with positioning bolts. The vertical energy-absorbing steel plate and the steel arch are positioned in the same direction and share the internal force of the structure.

2.3. Experimental Design

The ED studied in this paper is designed to support a large-deformation tunnel of soft rock in China. It is required to have a large deformation capacity and low stiffness. Therefore, this study designed a series of EDs to test their deformation capacity and mechanical properties. Figure 3 shows a linear energy-absorbing damper (LED); Figure 4 shows two kinds of arc energy-absorbing dampers (AED-I, AED-II).

Figure 3. Linear energy-absorbing damper (LED).
Influence factors such as the structure’s form and the welding position of the vertical energy-absorbing steel plates were considered. An electro-hydraulic servo universal material testing machine (WES-1000B) was used for the compression test, and the maximum load of this machine was 1000 kN (Figure 5).

Figure 4. Two kinds of arc energy-absorbing dampers: (a) arc energy-absorbing damper I (AED-I); (b) arc energy-absorbing damper II (AED-II).

Figure 5. Compression testing machine.
The test process was divided into two stages, each using the displacement loading method to load, as shown in Table 1.

**Table 1. Test process.**

| Stages | Loading Method   | Loading Speed | Target          | Target Value |
|--------|------------------|---------------|-----------------|--------------|
| I      | Displacement     | 5 mm/min      | Target displacement | 20 mm      |
| II     | Loading          | 10 mm/min     | Target displacement | 220 mm     |

Two specimens were tested for each case to avoid biased results, and the results were averaged. During the test, the compression displacement and the pressure on the specimen were recorded in real time.

**3. Results**

**3.1. Comparison of Preliminary Test Results**

**3.1.1. LED**

The compression–deformation process of the LED is shown in Figure 6. It shows that a bending deformation first occurred in the middle of the two vertical energy-absorbing steel plates in a symmetrical direction. With an increase in the displacement loading, the compression deformation of the specimen also continuously increases. Finally, the vertical energy-absorbing steel plate also shows bending deformation near the welding position.

![Figure 6. The compression–deformation process of the LED.](image)

The stress–deformation curve of the LED is shown in Figure 7. It consists of three stages: (1) elastic rising stage; (2) yield falling stage; (3) yield constant resistance stage.

1. **Elastic rising stage.** In this stage, the stress increases linearly with the compression deformation but is minimal, and the bending of the energy-absorbing steel plates is not apparent. Finally, the peak strength is 23.52 MPa.
2. **Yield falling stage.** In this stage, the stress decreases with the compression deformation, and the energy-absorbing steel plates yield and produce obvious bending deformation.
3. **Yield constant resistance stage.** In this stage, the stress remains constant and does not change with the compression deformation. The middle part of the energy-absorbing steel plates experiences a large bending deformation. The constant resistance is 3.50 MPa, and the total compression deformation is 206.00 mm.

![Figure 7. The stress–deformation curve of the LED.](image)
Figure 6. The compression–deformation process of the LED.

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The other specimen failed to produce corresponding data due to a mechanical failure of the testing machine during the loading process.

3.1.2. **AED-I**

The compression-deformation process of the AED-I is shown in Figure 8. The arc energy-absorbing steel plates bend to the same side.

The stress–deformation curve of the AED-I is shown in Figure 9. It also contains three stages: (1) elastic rising stage; (2) yield falling stage; (3) yield constant resistance stage.

The first specimen’s peak strength is 17.30 Mpa; its constant resistance is 3.50 Mpa; and its total compression deformation is 181.90 mm (AED-I-1). The second specimen’s peak strength is 13.36 Mpa; its constant resistance is 3.40 Mpa; and its total compression deformation is 183.92 mm (AED-I-2).

Figure 8. The compression-deformation process of the AED-I.

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3.1.3. AED-II

The compression-deformation process of the AED-II is shown in Figure 10. At the beginning of the test, the bending deformation of the two energy-absorbing plates pushes symmetrically inward. With an increase in the displacement loading, the bending deformation of the two energy-absorbing steel plates begins to expand to the same side. Finally, the compression state of the AED-II presents an irregular shape. The two connecting plates no longer remain parallel.

Figure 10. The compression-deformation process of the AED-II.
The stress–deformation curve of the AED-II is shown in Figure 11. The curve contains two peaks, both at the initial stage of deformation. During the deformation process, the collision of the two energy-absorbing steel plates of the AED-II causes the stress to rise again. The strength then rapidly drops and enters the constant resistance stage. The first specimen’s first peak strength is 17.41 Mpa; the second peak strength is 15.04 Mpa; its constant resistance is 5.30 Mpa; and its total compression deformation is 153.19 mm (AED-II-1). The second specimen’s first peak strength is 15.90 Mpa; the second peak strength is 15.74 Mpa; its constant resistance is 5.50 Mpa; and its total compression deformation is 152.30 mm (AED-II-2).

![Stress–deformation curve of AED-II](image)

Figure 11. The stress–deformation curve of the AED-IIs.

3.1.4. Comparison

The stress–deformation curve of the three steel dampers is shown in Figure 12. All of the test results are presented in Table 2. The compression ratio is the ratio of the maximum deformation of the energy-absorbing damper to the original height, which reflects the maximum deformation capacity of the energy-absorbing damper. The LED has the highest compression ratio. Still, its peak strength reaches 23.52 Mpa, close to the standard compressive strength of C25 concrete, with a safety factor of 1.63. It appears that the LED might not have been deformed, but instead, the concrete might have cracked and collapsed. The AED-I has the lowest peak strength and constant resistance. The arc-shaped steel plate gives the compression deformation specific directivity and controllability. The AED-II has two peaks and maximum constant resistance. In the process of compression, the bending deformation of the two energy-absorbing steel plates showed a certain randomness. Therefore, the AED-I was considered a preliminary scheme of soft-rock tunnel support by comparison in this study.

![Stress–deformation curve of three energy-absorbing dampers](image)

Figure 12. The stress–deformation curve of the three energy-absorbing dampers.

| Specimen Type | Initial Height (mm) | Average Value (mm) | First Peak Strength (Mpa) | Average Value (Mpa) | Second Peak Strength (Mpa) | Average Value (Mpa) | Constant Resistance (Mpa) | Average Value (Mpa) | Compressive Displacement (mm) | Average Value (Mpa) | Compressibility (%) | Average Value (%) |
|---------------|---------------------|--------------------|---------------------------|--------------------|---------------------------|--------------------|---------------------------|--------------------|---------------------------|--------------------|-------------------|-------------------|
| LED-1         | 250.00              | 250.00             | 23.52                     | 23.52              | -                         | -                  | 3.50                      | 3.50               | 206.00                    | 206.00             | 82.40             | 82.40             |
| LED-2         | 250.00              | 250.00             | -                         | -                  | -                         | -                  | -                         | -                  | -                         | -                  | -                 | -                 |
| AED-I-1       | 250.00              | 250.00             | 17.30                     | 15.33              | -                         | -                  | 3.40                      | 3.40               | 183.92                    | 183.92             | 73.60             | 73.60             |
| AED-I-2       | 250.00              | 250.00             | 13.36                     | 15.33              | -                         | -                  | 3.40                      | 3.40               | 182.91                    | 182.91             | 72.80             | 72.80             |
| AED-II-1      | 242.00              | 242.00             | 17.41                     | 15.04              | -                         | -                  | 3.50                      | 3.50               | 153.19                    | 153.19             | 63.50             | 63.50             |
| AED-II-2      | 244.00              | 244.00             | 15.90                     | 15.74              | 15.39                     | 15.39              | 3.50                      | 3.50               | 152.30                    | 152.30             | 62.40             | 62.40             |

Table 2. Test results.
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3.2. Further Optimization

Although the AED-I can be used in practical engineering, it can be further optimized to achieve more efficient energy absorption. It is necessary to reduce its peak strength and constant resistance further. Therefore, the bending radius of the energy-absorbing steel plate was reduced from 1800 mm to 1300 mm. Two optimized AED-Is (AED-IO-1, AED-IO-2) were made, and the compression test was carried out again. The test results are shown in Figure 13.

Table 3 shows the test results of the AED-IOs. After optimization, the deformation capacity of the AED-IO had increased to 75.79%, while the peak strength and constant resistance were reduced to 10.50 Mpa and 2.94 Mpa, respectively. Its safety factor increased to 2.38. These results indicate that the AED-IO could better release the surrounding rock pressure and absorb the energy accumulated in the surrounding rock.

Figure 13. The stress–deformation curve of the AED-IOs.
Table 3. Test results of the AED-IOs.

| Specimen Number | Peak Strength (Mpa) | Average Value (Mpa) | Constant Resistance (Mpa) | Average Value (Mpa) | Compressive Displacement (mm) | Average Value (Mpa) | Compressibility (%) | Average Value (%) |
|----------------|---------------------|--------------------|--------------------------|--------------------|-------------------------------|---------------------|---------------------|---------------------|
| AED-IO-1       | 10.25               | 10.50              | 2.95                     | 2.94               | 186.97                        | 189.46              | 74.79               | 75.79               |
| AED-IO-2       | 10.75               | 10.50              | 2.93                     | 2.94               | 191.94                        | 189.46              | 76.78               | 75.79               |

4. Case Study

4.1. Case Background

The Zhongshao Tunnel is a key project of the Yuchu Expressway. The Yuchu Expressway is located in Yunnan Province, a border region in southwest China, connecting Yuxi and Chuxiong (Figure 14).

![Study Area](image)

**Figure 14.** Study area.

The total length of the tunnel is 2135 m, and the maximum buried depth reaches 319 m. The tunnel was designed as a double-line, six-lane tunnel accommodating a speed of 100 km/h. This section is composed of IV-level surrounding rock, is buried 60~100 m, and is designed for an SF5a lining type. According to the actual situation on-site, the field test was finally carried out in section K29 + 914 ~ K29 + 944, at a length of 30 m. As shown in Figure 15, the initial support became unstable and collapsed. The replacement of the collapsed initial support resulted in a massive waste of supporting materials, soaring costs, and discharge of construction waste.

![Initial support structure collapsed](image)

**Figure 15.** The initial support structure collapsed.
4.2. Installation and Monitoring

First, mass-produced AED-IOs were pre-assembled outside the tunnel to ensure the smooth progress of subsequent construction inside the tunnel (Figure 16).

![AED-IO production and pre-assembly](image1)

Figure 16. AED-IO production and pre-assembly.

The AED-IOs were arranged at 22.5° of the steel arch’s left and right arch waists. The actual installation is shown in Figure 17.

![Actual installation: (a) connecting the steel arches; (b) filled with concrete](image2)

Figure 17. Actual installation: (a) connecting the steel arches; (b) filled with concrete.
The cumulative construction length of the AED-IOs is 30 m. Monitoring sections were set at 10 m and 20 m, and seven monitoring points were selected for each section (Figure 18). A pressure box and strain gauge were used to monitor the surrounding rock pressure and the axial force of the steel arch.

![Pressure box and strain gauge](image)

**Figure 18.** Monitoring points.

### 4.3. Results and Evaluation

The results of the surrounding rock pressure of the two monitoring sections are shown in Table 4.

| Monitoring Sections | Vault (Mpa) | Left Hance (Mpa) | Right Hance (Mpa) | Left Wall (Mpa) | Right Wall (Mpa) | Left Foot (Mpa) | Right Foot (Mpa) |
|---------------------|-------------|-----------------|-------------------|----------------|------------------|----------------|------------------|
| 10 m                | 0.025       | -               | 0.025             | 0.130          | -                | 0.010          | 0.002            |
| 20 m                | 0.011       | 0.010           | 0.010             | 0.060          | 0.001            | 0.026          | 0.025            |

The steel arch sensors of the second section (20 m) were damaged, so the data cannot be used. Table 5 only gives the statistical stress data of the steel arch of the first section (10 m).

| Monitoring Point    | Vault (Mpa) | Left Hance | Right Hance | Left Wall | Right Wall | Left Foot | Right Foot |
|---------------------|-------------|------------|-------------|-----------|------------|-----------|------------|
| Outer arc (Mpa)     | -86.14      | -91.15     | -9.89       | -122.26   | -20.01     | -52.75    | -23.94     |
| Inner arc (Mpa)     | -114.18     | -89.06     | -5.73       | -54.98    | -38.28     | -75.13    | -58.65     |

According to the on-site survey and monitoring results, the AED-IOs have undergone obvious compression deformation (Figure 19). The entire ring of the steel arch was under small eccentric compression, and the maximum compressive stress was 122.26 Mpa. The strength–safety factor of the support structure was greater than 1. On the other hand, the maximum surrounding rock pressure was only 0.13 Mpa, indicating that the surrounding rock pressure was fully released through the deformation of the AED-IOs.
In a traditional high-stiffness support, the amount of main construction waste caused by replacing the initial support in each meter of the tunnel is shown in Table 6. Since the AED-IOs can ensure the stability of the initial support, it does not need to be dismantled and replaced, so there will be no additional construction waste.

Table 6. Construction waste is generated by initial support replacement (traditional high-stiffness support).

| Construction Waste | Scrap Steel Arch (kg/m) | Scrap Steel Mesh (kg/m) | Scrap Steel Tube (kg/m) | Shotcrete Block (t/m) |
|--------------------|------------------------|------------------------|------------------------|-----------------------|
| Traditional support | 1903.17                | 310.62                 | 225                    | 18.34                 |

Table 7 compares extra costs between the replacement of the initial support and AED-IO adoption. The price of materials used reflects the general market price at the Zhongshao Tunnel site. Equipment cost includes equipment usage costs and the cost of depreciation. Staff salaries have been calculated according to the standard local wage of ordinary skilled workers: CNY 250 per day. The cost calculations show that for each meter of soft-rock tunnel with traditional support, the extra cost is CNY 24,654.35 due to the replacement of the initial support. However, the extra cost of adopting AED-IOs is only CNY 330.50.

Table 7. Comparison of extra costs.

| Support Type         | Steel (CNY/m) | Shotcrete (CNY/m) | Equipment (CNY/m) | Fuel (CNY/m) | Staff Salary (CNY/m) | Total (CNY/m) |
|----------------------|---------------|-------------------|-------------------|--------------|----------------------|---------------|
| Traditional support  | 12,193.95     | 3260.40           | 600               | 600          | 8000                 | 24,654.35     |
| Energy-absorbing     | – 87.50       | – 60              | 100               | 100          | 278                  | 330.50        |

In sum, compared with traditional support, the application of AED-IOs avoids the collapse and replacement of the initial support and enables safe construction. Meanwhile, in each meter of tunnel, AED-IOs reduced over 20 tons of construction waste, and saved CNY 24,323.85 of construction cost. The construction of soft-rock tunnels is moving towards a safer, more economical, and environmentally sustainable direction.

5. Discussion

When traditional high-stiffness support structures face the complex problem of soft-rock tunnel support, the initial support is prone to instability and collapse, resulting in construction delays, mass amounts of construction waste, and soaring costs. First, to solve this problem, this paper proposed an energy-absorbing support theory that uses...
deformation to release the stress from the surrounding rock. Furthermore, the pressure characteristics of the surrounding rock deformation were analyzed, and the design direction of the EDs was determined.

Next, three different EDs were designed, and compression tests were carried out. The test results showed that, although the LED had the highest deformation capacity, its peak strength was also the highest, which may cause deformation after the concrete has already cracked. The AED-I had the lowest peak strength and constant resistance; the AED-II had two peak strengths, its deformation capacity was the lowest, and its deformation morphology was irregular. Therefore, the AED-I was taken as a preliminary scheme of energy-absorbing support in this study.

Finally, the AED-I was further optimized to reduce the bending radius of the energy-absorbing steel plate. As a result, its peak strength and constant resistance were further reduced, and its deformation capacity was further improved, which could meet the support requirements of a soft-rock tunnel.

In soft-rock tunnels, when the stress of the surrounding rock exceeds the peak strength of a traditional high-stiffness support structure, instability failure will occur. Therefore, it can easily cause safety accidents, casualties, and equipment damage at the construction site. On the other hand, the collapsed support structure requires replacement, which will generate a great deal of construction waste and cause a serious waste of supporting materials and economic losses. This study designed a series of EDs with greater deformation capacity and less stiffness based on the energy principle. The coordinated deformation of EDs releases the energy accumulated in the surrounding rock. Compared with a traditional support, the application of AED-Ios avoids the collapse and replacement of the initial support. In each meter of tunnel, AED-Ios reduce over 20 tons of construction waste and CNY 24,323.85 of construction cost. Therefore, the research results of this paper have a specific guiding significance for promoting the safe, economical, and environmentally sustainable construction of soft-rock tunnels.

6. Conclusions

This paper designed a series of EDs based on the energy principle. A compression test evaluated the mechanical properties of each ED, and the structure parameters of the ED were further optimized. The AED-I designed in this study has been applied in the Zhongshao Tunnel. The major conclusions are as follows:

(1) Proposed a support design method of soft-rock tunnels based on the energy principle;
(2) A series of EDs with large deformation capacity and low stiffness were designed for soft-rock tunnel support based on the energy principle;
(3) The LED has the highest deformation capacity, but its peak strength is also the highest; the AED-I has the lowest peak strength and constant resistance; the AED-II has two peak strengths, its deformation capacity is the lowest, and deformation morphology is irregular;
(4) After optimization, the deformation capacity of the AED-I increased to 75.79%, while the peak strength and constant resistance were reduced to 10.50 Mpa and 2.94 Mpa, respectively;
(5) Compared with a traditional support, the application of AED-Ios avoids the collapse and replacement of the initial support. In each meter of tunnel, AED-Ios reduce over 20 tons of construction waste, and CNY 24,323.85 of construction cost;
(6) The AED-Io ensured construction safety, reduced the amount of construction waste, and decreased extra costs.

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