Coupled static and dynamic tensile property of granite

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Abstract. The principle of coupled static and dynamic loading is illuminated according to the basic principle of the SHPB, i.e., one-dimensional stress wave propagation and uniformity of the specimen. In the Tianhu area of Xinjiang Province, which is a preselected area for high-level radioactive waste geological disposal, a series of coupled static and dynamic loading was conducted in a borehole. The dynamic tensile strength could reach a maximum level when the axial tensile stress is about 50% of the static tensile strength. Meanwhile, as the axial tensile stress increases, the coupled static and dynamic tensile strength increases obviously, reaching about three times the static tensile stress and about 1.5 times the dynamic tensile strength. The failure model of the coupled test is a tensile failure pattern, which is the same as in the static tension and conventional dynamic loading test. Furthermore, through a series of coupled static and dynamic loadings, the strength of the rock specimen could be obtained under different kinds of axial tensile stress and dynamic loading. Thus, the critical value of the dynamic loading could be confirmed, which is useful for blasting excavation in deep geotechnology.

1. Introduction

High-level radioactive waste has a long half-life cycle and high toxicity. The disposal of high-level radioactive waste is a challenge faced by nuclear-weapon states. At present, the widely considered feasible method of high-level radioactive waste disposal is deep geological disposal. To ensure the effective isolation of the biosphere for a few thousand years or even longer, high-level radioactive waste is buried in a geological body that is stable to the surface of about 500–1000 m. With its preferable stability, high strength, and low permeability, granite is considered an ideal surrounding rock for high-level radioactive waste geological disposal and is the main candidate as surrounding rock for geological disposal in China [1,2].

Before project excavation, a rock is in a certain in-situ stress state, that is, it is in a static stress state before bearing dynamic load, which is a typical static and dynamic coupled loading problem. Aside from being affected by high crustal stress, the rock is superimposed by dynamic loads such as mining disturbance and even earthquakes. Considering only the static load or the dynamic load is not enough for studying rock engineering. Doing so can sometimes meet actual engineering requirements, but it is still insufficient in some cases. The construction of a high-level radioactive waste geological disposal site in a deep area is usually in a higher two-dimensional and three-dimensional stress state.

The failure process of rock under dynamic load can be approximately simulated by the coupling of static and dynamic load, which is more practical than when only the action of dynamic load or the static load is considered. At present, the testing method and result analysis of rock failure for the coupled static and dynamic loading are relatively insufficient, thus requiring further study [3-13]. This
index should be studied in depth and measured carefully because the coupled static and dynamic strength of the rock could reflect the mechanical property and engineering performance well. At present, research on coupled static and dynamic loading mainly studies the failure mechanism and pattern of one-dimensional coupled compression loading. Theoretically, the damage, catastrophe, fracture mechanism, constitutive model, and failure criterion of rock under coupled compression loading were studied. However, experimental studies conducted under coupled static and dynamic tensile loading are relatively inadequate [14-26].

The Tianhu area of Xinjiang Province, as one of the preferred areas for the geological disposal of high-level radioactive waste in China, is gradually becoming a focus of research because of the mechanical properties of granite in this area. Any high-level radioactive waste geological disposal site must have a complete rock mass, high mechanical strength, low permeability, and low in-situ stress.

One-dimensional coupled static and dynamic tensile loading tests are conducted for the granite in a borehole to obtain a preliminary understanding of the rock mechanical properties.

2. Principle of one-dimensional coupled static and dynamic testing

One-dimensional coupled loading involves applying a certain amount of static load along the axial direction on the specimen first. Then, the impact load along the axial direction is forced together with the static load. The applied static load can be confirmed by the uniaxial compressive strength or tensile strength according to the static uniaxial compression test or static tensile test. These static values are used as a reference for the dynamic load. Generally, the static values have a certain ratio of axial pre-pressure values of coupled static and dynamic testing. The loading model is shown in Figure 1.

\[
\sigma = \frac{p_s}{A}
\]

\[
p_s = p_{as} + p_d
\]

\[
p = p_t
\]

\[
p_{as}
\]

\[
p_d
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\[
0
\]

\[
0
\]

\[
\varepsilon
\]

\[
t
\]

(a) Mechanical model under static loading

(b) Mechanical model under dynamic loading

**Figure 1.** Schematic of rock model under static and dynamic loading

Figure 1 shows that the coupled static and dynamic loading is actually a combination of conventional static load test with the dynamic test. When the axial impact load is not applied, it is a simple static test. When the axial load is zero, it is a general impact test. When the axial load is pre-pressured first, then a dynamic load is impacted, it is a coupled loading test.
In this study, an SHPB device is used to study the dynamic characteristics of rock samples under moderate strain rate loading. The test principle under the condition of one-dimensional coupled static and dynamic loading also needs to satisfy the two basic assumptions of SHPB, that is, one-dimensional stress wave propagation in the elastic bar and stress homogenization of the specimen.

For the first assumption, i.e., one-dimensional stress wave propagation in the elastic bar, the stress wave follows the one-dimensional propagation law in the elastic bar. When the elastic wave propagates in a slender bar, the dispersion effect will occur due to the transverse inertia effect. A theoretical discussion suggests that, from an infinite sine wave, the velocity of the wave \( C_p \) as obtained by the wave equation and mathematical deduction is [27,28]

\[
C_p = \left[ 1 - \mu^2 \frac{\pi^2}{\lambda^2} \right] C_0 \quad (1)
\]

where \( C_0 \) is the one-dimensional longitudinal wave velocity, \( \lambda \) is the wave length, \( \mu \) is the Poisson’s ratio, and \( r \) is the radius of the cylinder bar. The above equation shows that the propagation speed of a high-frequency wave corresponding to a short wave is low, whereas the propagation speed of a low-frequency wave related to a long wave is high.

Any linear elastic wave can be viewed as a superposition of harmonic components at different frequencies, which can propagate each other according to their own phase velocity, so the wave cannot remain in its original form and the wave diffusion phenomenon occurs. Moreover, it can be eliminated as much as possible from the geometric size of the elastic bar. It can be minimized to realize the one-dimensional stress wave propagation in the elastic bar by the controlled value \( \frac{r}{\lambda} \), in which \( \frac{r}{\lambda} \leq 1 \) should be satisfied.

Only the dispersion effect of the stress wave is restrained. The strain measured by the strain gauge on the surface of the incident bar and the transmission bar can represent the internal strain of the bar. The stress and strain measured in the middle of the elastic bar can represent the stress and strain at both ends of the specimen.

The dispersion effect of the stress wave in the elastic bar is eliminated as much as possible, which can be satisfied with the one-dimensional stress wave state, so that the stress wave signal at a certain distance from the bar end can be used instead of that at the end of the bar.

However, some research considered that one-dimensional stress state should be ensured not only in the elastic bar but also in the specimen [29,30]. It is a more rigorous assumption for the SHPB system, thus ensuring that the whole testing system is completely in a one-dimensional stress state. In fact, as mentioned above, it is satisfied only if the one-dimensional stress wave assumption is applied in the bar. All in all, the aim is to obtain the real force at both ends of the specimen.

Furthermore, the specimen is in a one-dimensional stress state. How to verify the state should be discussed to clarify the load on the specimen.

For the fractured specimen, the stress wave propagation no longer follows the one-dimensional stress state. The specimen is in the three-dimensional stress state. Another assumption is thus proposed, which is the dynamic force balance in the specimen. If the forces on both ends of the specimen are equal, then the incident stress wave can move back and forth in the specimen several times and into the transmitted bar, so that the stress wave can be proved in the one-dimensional state.

In this way, not only the one-dimensional assumption of the stress wave in the elastic bar but also that in the specimen are satisfied. Therefore, the whole SHPB system is in the ideal one-dimensional stress state. A detail that should be mentioned is that the purpose of this assumption is to obtain the exact force at both ends of the specimen.

Essentially, whether the assumption is the existence of a one-dimensional stress wave in the elastic bar or in the specimen, the essences are all consistent, thereby ensuring the accurate measurement of the stress at both ends of the specimen. If only the assumption is satisfied in the bar, then the stress wave can no longer guarantee one-dimensional propagation when transmitted from the specimen to
the transmitted bar. Therefore, the one-dimensional assumption should apply in the elastic bar and in the specimen. These two assumptions of one-dimensional stress wave propagation are consistent with each other. For the coupled static and dynamic loading, it would be suitable as long as the above two basic assumptions can be satisfied.

3. Testing progress

3.1. SHPB equipment

The dynamic parameter was achieved by using SHPB system with a 75 mm diameter (Figure 2), which is designed by Central South University.

![Figure 2. Schematic of the SHPB setup](image)

A stable semi-sinusoidal wave is required to eliminate the P-C oscillation, which means that the rising segment of the loading wave should settle in about 100 μs. A spindle-type impact bullet is used in the emitter. The material and the maximum diameter of the bullet are the same as those that correspond to the incident and transmission bars, and the constant strain rate can be realized by the produced semi-sinusoidal stress wave. The parameters of the SHPB are illustrated in Table 1.

| Parameters of SHPB | Diameter of the bar /mm | Length of the input bar /mm | Length of the output bar /mm | Elastic modulus /GPa | Longitudinal wave velocity /m/s | Poisson’s ratio | Pressure /MPa | Density /kg·m⁻³ |
|--------------------|--------------------------|-----------------------------|----------------------------|----------------------|-----------------------------|----------------|---------------|----------------|
|                    | 75                       | 2000                        | 2000                       | 250                  | 5400                        | 0.285          | 0–10          | 7810           |

3.2. Specimen preparation

Granite with good integrity and homogeneity is selected. The core is drilled at a depth of about 360 m, and the specimen numbers are uniformly numbered in the order of 360-X. The samples are manufactured according to the conventional specimen requirement for rock mechanics.

A rock core drilling machine, cutting machine, and grinding machine should be used for fine processing to prepare the specimen to meet the testing standard. According to the standard of the rock
testing method GB/T 50266-99[31], all the test specimens are uniformly processed into a cylinder with a standard size. The specimen for the static tensile and dynamic mechanical testing is a Brazilian disc, which has a size of about $\Phi 50 \text{ mm} \times H25 \text{ mm}$, corresponding to diameter $\times$ height. The geometric size, density, and longitudinal wave velocity of the processed specimens were measured. A part of the rock specimen is shown in Figure 3.

![Figure 3. Rock specimen](image)

3.3. Testing steps

The coupled dynamic and static strength under different impact loading rates and static loads is examined through one-dimensional static and dynamic coupled impact test. The coupled loading test proceeds as follows:

(1) The axial pre-static load of different levels is designed according to the static tensile strength. Then, the dynamic tensile strength of the rock specimen under the condition of two to four fractal blocks is selected as the pure dynamic tensile strength for the coupled test.

(2) A sample scratched with Vaseline on both sides is placed between the incident bar and the transmitted bar. The axial pressure system is adjusted, and the manual pump is connected to the axial static pressure loading device. Then, the predetermined axial static load could be applied.

(3) With the pure dynamic tensile strength taken as reference, the impact pressure and the position of the punch in the emission chamber are selected, and pre-impacting is conducted on the specimen for each axial compression. The dynamic test was repeated under different impact velocities with the same impact pressure and punch position.

(4) The signal is selected and saved by the data acquisition system. The above steps are repeated to complete the series of tests.

(5) The impact tests under different impact loads are conducted on the basis of the selected first type of axial pressure. Afterward, the impact load test of the second type of axial pressure is carried out.

The impact pressure of the punch and the impact velocity under the first type of axial pressure are roughly the same as those under the second type. Thus, comparing and analyzing the impact data under different axial compression pressures and loading conditions would be suitable.

3.4. Static tensile testing

The static tensile strength of the rock samples must be determined to compare the mechanical parameters between the static loading and the dynamic loading, and to refer for the determination of the presupposed axial pressure value of the coupled static and dynamic loading. The specimen was placed in a special fixture to load. The testing was controlled by displacement loading, and the loading rate was 3 mm/min. Then, the specimen was loaded until failure, and all the data was recorded. Finally, the tensile strength can be obtained using the Brazilian tensile formula. The morphology after static tensile failure is shown in Figure 4.

![Figure 4. Morphology after static tensile failure](image)
Figure 4. Tension testing of the rock specimen

The rock failure occurred mainly along the loading direction, and the morphology is an approximately symmetrical semicircular disc. The average tensile strength of the rock samples is 11.75 MPa, which is then taken as the static tensile strength of all rock samples.

3.5. One-dimensional static and dynamic coupled testing

The reference of static tensile strength and pure dynamic tensile strength of the rock specimen indicates that the controlled impact pressure is 0.3, 0.32, 0.35, 0.38, 0.40, 0.42, and 0.45 MPa. The axial static load under the impact dynamic load is 3.53, 5.88, 8.23, and 10.58 MPa, corresponding to 30%, 50%, 70%, and 90%, respectively, of the peak static tensile strength. The specimen held by the two bars is shown in Figure 5.

Figure 5. Schematic of the rock under dynamic loading

When the axial static pressure is relatively small, the elastic modulus increases because the inner part of the specimen has been compressed and closed before the impact. The specimen is still under an elastic state after the shock. However, when the axial static pressure is large, the microcrack in the sample is in the stage of expansion and connected before the impact. Therefore, the stress–strain curve at this time is presumed to have no initial approximate elastic stage and directly enters the nonlinear stage when it is impacted.

The dynamic tensile strength could be calculated using the static tensile strength formula. A prerequisite for this process exists: For the dynamic tensile testing, the dynamic force balance must be verified, i.e., the stress on both end faces of the specimen should be almost the same. This condition means that the inertial effect of the rock specimen could be ignored and the one-dimensional wave propagates along the experimental device.

4. Testing results and analysis

4.1. Testing result of coupled static and dynamic testing

The coupled static and dynamic tensile test results are shown in Tables 2–5. Under the same static load and different dynamic load, the coupled tensile strength is about 80%–280% higher than the static tensile strength. For the same axial pressure, the dynamic tensile strength increases with the loading rate.

4.2. Mechanical property of dynamic strength

The tensile strength is of great significance for engineering. From a microscopic perspective, the failure modes of rock are mostly caused by the tensile. In combination with the static tensile test and the SHPB impact tensile test, the relationship between the dynamic tensile strength and the loading rate under different static tensile pressures and impact loadings is described as follows.
Figure 6. Relationship between dynamic tension and loading rate under 3.53 MPa static pressure

The relationship between dynamic tensile strength and loading rate under a static axial tensile pressure of 3.53 MPa and different impact loading is shown in Figure 7. The dynamic tensile strength increases with the loading rate. When the loading rate ranges from $0.29 \times 10^6$ MPa/s to $0.45 \times 10^6$ MPa/s, the dynamic tensile strength increases obviously from 17.7 MPa to 23.18 MPa. However, when the loading rate ranges from $0.55 \times 10^6$ MPa/s to $0.63 \times 10^6$ MPa/s, the dynamic tensile strength is maintained at about 23 MPa, which is more stable.

Table 2. Testing result of the dynamic and static coupling tension test when the static pressure is 3.53 MPa

| No.  | D/mm | B/mm | m/g  | $\rho$/kg/m$^3$ | $V_p$/m/s | t/μs | $\sigma_d$/MPa | Loading rate /10$^6$ MPa/s |
|------|------|------|------|-----------------|------------|------|----------------|---------------------------|
| 360-8 | 48.26 | 26.86 | 128.50 | 2616.69         | 5595.83    | 46.00 | 19.22          | 0.42                      |
| 360-9 | 48.25 | 27.02 | 130.00 | 2632.65         | 5404.00    | 51.00 | 23.18          | 0.45                      |
| 360-10| 48.32 | 26.45 | 125.50 | 2588.78         | 5397.96    | 41.00 | 23.11          | 0.56                      |
| 360-11| 48.20 | 27.39 | 131.00 | 2622.50         | 4722.41    | 40.00 | 23.75          | 0.59                      |
| 360-12| 48.37 | 26.46 | 125.00 | 2572.16         | 4725.00    | 36.00 | 22.59          | 0.63                      |
| 360-13| 48.18 | 26.85 | 129.50 | 2646.81         | 5163.46    | 43.00 | 23.68          | 0.55                      |
| 360-14| 48.29 | 26.40 | 127.00 | 2627.94         | 5387.76    | 61.00 | 17.70          | 0.29                      |

Table 3. Testing result of the dynamic and static coupling tension test when the static pressure is 5.88 MPa

| No.  | D/mm | B/mm | m/g  | $\rho$/kg/m$^3$ | $V_p$/m/s | t/μs | $\sigma_d$/MPa | Loading rate /10$^6$ MPa/s |
|------|------|------|------|-----------------|------------|------|----------------|---------------------------|
| 360-15| 48.25 | 25.37 | 122.50 | 2642.11         | 4974.51    | 57.00 | 10.35          | 0.18                      |
| 360-16| 48.26 | 26.58 | 129.00 | 2654.55         | 5424.49    | 53.00 | 18.30          | 0.35                      |
| 360-17| 48.33 | 27.30 | 131.00 | 2617.01         | 5571.43    | 45.00 | 14.25          | 0.32                      |
| 360-18| 48.22 | 27.13 | 130.50 | 2635.34         | 4932.73    | 60.00 | 18.56          | 0.31                      |
| 360-19| 48.30 | 26.81 | 129.50 | 2637.60         | 4622.41    | 36.00 | 21.07          | 0.59                      |
| 360-20| 48.27 | 27.22 | 130.50 | 2621.19         | 5444.00    | 50.00 | 17.66          | 0.35                      |
| 360-21| 48.26 | 26.18 | 125.00 | 2611.54         | 5236.00    | 39.00 | 19.32          | 0.50                      |

Table 4. Testing result of the dynamic and static coupling tension test when the static pressure is 8.23 MPa

| No.  | D/mm | B/mm | m/g  | $\rho$/kg/m$^3$ | $V_p$/m/s | t/μs | $\sigma_d$/MPa | Loading rate /10$^6$ MPa/s |
|------|------|------|------|-----------------|------------|------|----------------|---------------------------|


360-22 48.22 27.12 130.50 2636.31 5424.00 49.00 16.32 0.33
360-23 48.23 26.59 127.50 2625.96 5016.98 49.00 12.29 0.25
360-24 48.19 26.93 128.00 2607.29 5495.92 38.00 11.44 0.30
360-25 48.24 26.90 129.50 2635.32 5380.00 97.00 10.67 0.11
360-26 48.20 27.23 131.00 2637.91 5339.22 61.00 17.57 0.29
360-27 48.15 26.63 128.50 2651.37 5262.00 50.00 17.46 0.35

**Table 5.** Testing result of the dynamic and static coupling tension test when the static pressure is 10.58 MPa

| No. | D/mm | B/mm | m/g | ρ/kg/m³ | Vp/m/s | t/μs | σd/MPa | Loading rate /10⁶ MPa/s |
|-----|------|------|-----|---------|--------|------|---------|--------------------------|
| 360-28 | 48.17 | 26.75 | 129.00 | 2647.54 | 5144.23 | 75.00 | 19.35 | 0.26 |
| 360-30 | 48.18 | 26.65 | 129.00 | 2656.37 | 5028.30 | 41.00 | 23.62 | 0.38 |
| 360-31 | 48.19 | 27.16 | 131.50 | 2655.90 | 5223.08 | 37.00 | 14.37 | 0.39 |
| 360-32 | 48.22 | 26.90 | 129.50 | 2637.51 | 5723.40 | 45.00 | 24.10 | 0.54 |
| 360-33 | 48.20 | 25.90 | 124.50 | 2635.76 | 5510.64 | 36.00 | 19.14 | 0.53 |
| 360-34 | 48.26 | 27.02 | 129.50 | 2621.44 | 5514.29 | 54.00 | 18.02 | 0.33 |

**Figure 7.** Relationship between dynamic tension and loading rate under 5.88 MPa static pressure

The relationship between dynamic tensile strength and loading rate under an axial pressure of 5.88 MPa and different dynamic loading is shown in Figure 8. The dynamic tensile strength also increases with the loading rate. When the loading rate ranges from $0.18 \times 10^6$ MPa/s to $0.59 \times 10^6$ MPa/s, the dynamic strength increases from 10.35 MPa to 21.07 MPa. However, when the loading rate is around $0.31 \times 10^6$ MPa/s, the dynamic tensile strength remains at about 18.56 MPa. This result occurred because the specimen did not completely crack at the beginning of the impact load, thus leading to a slightly long impact time, which induces a slightly low loading rate and a slightly high dynamic loading strength.
The relationship between dynamic tensile strength and loading rate under an axial pressure of 8.23 MPa is shown in Figure 9. The dynamic tensile strength also increases with the loading rate. When the loading rate ranges from $0.11 \times 10^6$ MPa/s to $0.35 \times 10^6$ MPa/s, the dynamic strength increases from 10.67 MPa to 17.46 MPa. However, when the loading rate is $0.3 \times 10^6$ MPa/s, the dynamic tensile strength remains at 11.44 MPa because a crack is initiated in the specimen, thus weakening the bearing capacity. Under dynamic impact, the rock quickly reaches the maximum capacity and is destroyed. Thus, the impact time is relatively short and the loading rate is higher, which indicates that the dynamic tensile strength is low.

The relationship between dynamic tensile strength and loading rate under axial pressure of 10.58 MPa is shown in Figure 10. The dynamic tensile strength also increases with the loading rate. When the loading rate ranges from $0.26 \times 10^6$ MPa/s to $0.58 \times 10^6$ MPa/s, the dynamic tensile strength increases obviously from 19.35 MPa to 23.62 MPa. However, when the loading rate is $0.39 \times 10^6$ MPa/s, the dynamic tensile strength remains at 14.37 MPa, which is due to the pre-initiated microcrack induced by the higher axial pressure. Then, under the dynamic impact loading, the rock quickly reaches the maximum strength and is destroyed. Meanwhile, the impact time is relatively short, which indicates that the loading strength is slightly low.

In conclusion, the dynamic tensile strength increases with the loading rate, and the maximum dynamic tensile strength can reach three times the static strength. This condition actually reflects the rate-dependent effect of rock materials. The strain and loading rates are also different for diverse loading levels.

4.3. Mechanical property of coupled static and dynamic strength
The specimen is still in the elastic stage under a small axial static load. At this time, the ability of the specimen to withstand coupled static and dynamic load is gradually enhanced as the static load increases. This enhancement can be considered as the strengthening effect of coupled loading on rock materials. The axial static load plays a role in restraining the microcrack propagation. For the crack plane perpendicular to the axial static load direction in particular, if no axial static loading occurs, then
the dynamic impact wave will reflect on its surface and become the tensile wave, driving the crack expansion. However, when the axial static loading is stored, the crack gap is closed and the stress wave can be transmitted with no reflection, thereby greatly suppressing the deterioration of rock strength.

When the axial static pressure is large, the microcracks in the rock are not only completely closed, but internal damage also begins to occur, and new microcracks are gradually produced. When the stress wave is loaded, the tensile waves reflected by the incident wave on the surface of the crack further aggravate the expansion, nucleation, and propagation of the microcracks, thereby leading to the decline in the rock strength.

This paper defines that the coupled static and dynamic tensile strength is equal to the sum of the axial static tensile pressure and the dynamic tensile strength.

\[ \sigma_c = \sigma_{as} + \sigma_d \]  

(2)

where \( \sigma_c \) is the coupled static and dynamic tensile strength, \( \sigma_{as} \) is the axial static tensile pressure, and \( \sigma_d \) is the dynamic tensile strength.

With a rock that has a similar loading rate of \( 0.3 \times 10^6 \) MPa/s taken as an example, the coupled static and dynamic tensile strength and dynamic tensile strength with the static tensile pressure are shown in Fig. 10.

When the axial static pressure is small, such as 3.53 MPa, the dynamic strength is increased by about 50% compared with the static strength. When the axial static pressure is 5.88 MPa, the dynamic strength reaches the maximum of 18.56 MPa, which is about 80% higher than the static strength. Meanwhile, the axial static pressure is 50% of its static strength. However, when the axial static pressure is 8.23 and 10.58 MPa, the dynamic tensile strength does not show an obvious growth trend and is maintained at around 18 MPa. If the axial static pressure is about 50% of the static tensile strength, then the internal particles of the rock contact closely and the inner cracks and voids are compressed to the maximum extent, but no new microcracks are produced. At this point, the rock is in a critical stress state, and it should absorb enough energy to break.

According to the trend of the coupled static and dynamic tensile strength, the coupled strength is 21.23 MPa when the axial pressure is 3.53 MPa, which is the minimum value of the coupled strength. When the axial pressure is 10.58 MPa, the coupled strength is 28.6 MPa, which is the maximum value. As a whole, the trend of the curve is increasing.

**Figure 10.** Rock strength under coupled loads and impact failure strength with different axial pre-compression stress

Simultaneously, the coupled static and dynamic strength not only increases with the axial static pressure but also increases with the dynamic tensile strength, which can reach three times the static tensile load and 1.5 times the dynamic tensile load. This condition reflects not only the rate-dependent effect of rock materials but also the very special mechanical properties under the coupled static and dynamic loading condition. A large static load that is withstood by the rock corresponds to a greater coupled static and dynamic tensile strength, which is enhanced by the static tensile strength. However, the dynamic tensile strength increases first and then decreases gradually under the static pressure.
4.4. Splitting process under the coupled loading

Usually, rock failure is the result of the propagation and interaction of microcracks. The failure model reflects the rock stress state; thus, analyzing the failure mode is of great significance. The static loading test shows that the failure pattern is split along the middle of the specimen [32-37]. The conventional SHPB impact tensile test and coupled static and dynamic test also show that the failure is split from the specimen center[38-43]. For the failure mode under coupled static and dynamic tensile loading, whether it is still in accordance with the mode of the static tensile test and conventional dynamic tensile test needs to be studied. Another good approach is to use a high-speed camera to shoot the whole failure process of the specimen under coupled static and dynamic loading.

At the initial stage of impact loading, cracks are initiated under the coupled static and dynamic load, resulting in a few microcracks, and the cracks are located in the center of the specimen. With the loading process, the stress wave is reflected back and forth inside the specimen, which leads to the expansion of the initial crack followed by its rapid extension. The crack extension direction is always along the central part of the specimen and finally extends to the two ends. As the loading continues, the specimen is ruptured in two halves along the central direction.

An observation of the failure mode of rock under coupled tensile loading tests shows that the main failure modes are divided into several patterns as follows: When the axial tensile pressure is zero or less, if the impact load is not large, then the rock often breaks into two halves or a few blocks. Meanwhile, the number of blocks increases with the loading rate. When the dynamic load is large, the rock will break into numerous rock crumbs. When both the axial static tensile pressure and the dynamic load are relatively large, the specimen will be crushed in a similar manner as rock burst, accompanied with a great noise. The fragments will splash now, with uniform and fine fragment particles. Therefore, the failure mode under coupled static and dynamic tensile loading is a tensile failure pattern.

5. Conclusions

(1) The principle of one-dimensional coupled static and dynamic loading test was studied by using the SHPB device. The suitability of coupled testing was illuminated from two aspects: one-dimensional stress wave transfers in the elastic bar and stress homogenization of the specimen.

(2) For the rock borehole in the Tianhu area of Xinjiang, the dynamic tensile strength increases first and then decreases with the axial tensile pressure under coupled static and dynamic tensile loading. At about 50% of the static tensile strength, the dynamic tensile strength reaches the maximum. However, the coupled static and dynamic tensile strength increases rapidly with the axial tensile pressure, which can reach three times the static tensile strength and 1.5 times the dynamic tensile strength.

(3) The failure mode under coupled static and dynamic tensile loading is a tensile failure pattern, which is consistent with that of the static and dynamic tensile tests.

(4) Through coupled static and dynamic loading, the critical loading value under different axial static pressures and impact loads can be obtained, thus providing theoretical guidance for blasting excavation in deep underground engineering. The rock material itself is a much more complex media, which is why it still needs to be studied systematically.

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