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*Research Article*

# Study on the Rock Size Effect of Quasistatic and Dynamic Compression Characteristics

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To study the size effect of rock under quasistatic and dynamic conditions, the changes in compressive strength with the change in specimen size are measured. Cylindrical granite specimens with length-diameter ratios in the range of 0.5~1 are used for uniaxial compression tests using an RMT testing machine and an SPHB impact testing machine. Under quasistatic loading, the failure modes of the specimens with different length-diameter ratios are different. The larger the size of the specimen structure is, the greater the probability of defects such as joints and micro cracks is and the smaller the influence of the specimen on the distribution of a three-dimensional stress state is. The rock strength decreases with increasing length-diameter ratio. Using the improved Weibull formula, the size of the specimen is expressed by the volume, and the calculated rock strength of different volumes is similar to the compressive strength from the quasistatic tests. Under dynamic loading, the dynamic compressive strengths of the specimens with different length-diameter ratios are similar, and the failure mode of the specimens is different from that under quasistatic loading. Soon after a crack appears in a specimen, the specimen splits. As the size of the specimens decreases, the fragments size to approach the millimeter scale. By improving the Weibull distribution formula and considering variation in strain rate caused by the size of the specimen, the dynamic compressive strength of rocks of different volumes is calculated by introducing the critical strain rate and related parameters, and the results are similar to the experimental dynamic compressive strength obtained. The improved Weibull formula based on the strength size effect can accurately describe the quasistatic and dynamic compressive strength laws.

## 1. Introduction

In underground engineering, excavation will cause deformation of surrounding rock [1, 2]. The rock size effect indicates that the rock mechanical properties representing strength are not constant with increasing size. Size effect is an inherent property of quasibrittle materials such as rock and concrete, possibly due to their inhomogeneity and existence of internal defects such as cracks, joints, and weak surfaces. Under quasistatic loading conditions, there are three widely accepted rules of size effect theories: Weibull [3] initially proposed statistical size effect theory based on the randomness of material strength, and it was widely applied [4] to explain the size effect phenomenon of quasibrittle rock structures. Based on the fracture energy release and fracture zone model, Bavavant [5, 6] proposed a size effect theory for fracture mechanics, which is not convenient to use in practice and does not conform to the size effect laws for materials with large size. Carpinteri [7, 8] proposed multifractal size effect theory based on the fractal concept in classical solid mechanics. Bažant [9] pointed out the limitations of multifractal size effect theory: (1) Most of the energy is not expended on the final fracture surface, so the fractal properties of the final fracture surface do not reflect the fractal nature of the material. (2) The dependence of the coefficients of the multifractal size effect law on the structure geometry cannot be explained by the fractal theory; that is, the applicability of the multifractal size effect law in the structure is insufficient. The dynamic size effect is obviously different from the quasistatic size effect. At the same strain rate, dynamic strength increases with increasing specimens' size, and larger specimens show a more significant strain rate effect. In the context of a complex microstructure hierarchy and finiteness of the crack growth rate, the relationship between the strength, strain rate, and specimen size has always been the focus of research [10–13]. Although the strength enhancement of materials under impact loading has been shown to be size-dependent, the effect of size on the dynamic material properties is still unclear. In addition, the law of the size effect of rock materials under impact load has not been fully understood, so it is urgent to expand the applicability of the size effect law.

Through different experimental methods or relevant theories, many scholars have obtained laws and empirical formulas that describe the relationship between material strength and size. Liu et al. [14], based on a large number of rock tests, summarized the test, summarized the rock strength test for specimens of different volumes, and sorted out a set of empirical formulas for the size effect of the strength of rock materials. Yang et al. [15] calculated a set of theoretical models that describe the size effect of rock materials with the results of quasistatic compression tests of marble of different sizes. Based on the weakest chain model and Poisson distribution hypothesis of defects, Zhang et al. [16] established a statistical model and general expression of the failure probability and strength size effect of quasibrittle materials under quasistatic loading by integrating volume and material factors. Both the empirical and theoretical models obtained by Liu et al. [14–16] can be used to calculate the quasistatic compressive strength of rocks to a certain extent but cannot be applied to rocks under dynamic loading conditions. Wang et al. [17] conducted experiments on three sizes of roller compacted concrete (RCC) under different strain rates with SHPB and proposed an empirical formula for the dynamic strengthening factor (DIF) of the compressive strength of roller compacted concrete (RCC), which can be used to predict the material strength strengthening under different strain rates. Zhang et al. [16] studied rock specimens of a unified size with "static-quasistatic-dynamic range" compression testing, and the rule of the mechanical parameters of rock was examined with the strain rate effect, and they summarized a unified model of the dynamic enhancement factor based on strain rate and loading rate from low to high loading scale; the model overcomes the deficiency of the traditional dynamic enhancement factor model in different loading rate. Some scholars [17, 18] took into account the total strain rate to calculate the strength of a single size of rock specimen under static and dynamic conditions, but they did not consider the change in rock strength with the specimens' size. Based on the Weibull distribution function, Wang et al. [19] introduced volume parameters and strain rate related parameters and considered the influence of the material size and strain rate effect to better elaborate the dynamic compressive strength rule of roller compacted concrete (RCC). The relative parameters in the formula are not suitable for rock materials.

The international code for the change in strength caused by change in strain rate was proposed for concrete [20], and there are many studies on related size changes [10, 21]. For many rock materials, many scholars have proposed many formulas for the size effect of strength based on experiments or theories, but there is no universal formula for size effect which can meet the conditions of quasistatic and dynamic loading. An improved formula based on the Weibull distribution function [16, 19] was applied to rock material under quasistatic and dynamic conditions. The relevant rock parameters were determined through tests and related studies, and the application effect was verified, to link the size effect of rock under quasistatic and dynamic conditions. Two important characteristics of rock materials under quasistatic conditions are the dispersion and size effect. Under dynamic conditions, the characteristics of rock materials are affected by the strain rate effect in addition to the dispersion and size effect. This is related to the existence of a large number of microscopic defects, such as random gaps and different holes in the rock material. The uncertainty of material strength can be analyzed by probability statistics theory. The Weibull distribution was the first to be defined by the concept of the weakest chain to analyze and describe the size effect phenomenon of strength and has been widely used. According to this theory, the strength of a material is determined by the strength of its weakest chain; that is, when the stress at a certain point exceeds the defect strength at that point, failure will occur. Zhang et al. [16] applied the Weibull distribution to various quasibrittle materials, all of which could reflect the size effect rule of material strength, indicating that the size effect formula using the Weibull distribution under quasistatic conditions is universal. Wang et al. [19] applied the Weibull distribution to the dynamic loading of concrete and added relevant volume and strain rate parameters to obtain a formula of the size effect law for roller compacted concrete (RCC), which proved the reliability of the Weibull distribution in the study of the size effect law in dynamic loading. As a heterogeneous material, the failure process of granite includes compaction, elastic deformation, stable failure, and unsteady failure. The strength of granites of different size has an obvious size effect rule, and the Weibull formula is used to explain the size effect rule. Based on the Weibull distribution theory, the quasistatic and dynamic size effects of rock materials are interrelated.

## 2. Rock Specimens Preparation and Experimental

*2.1. Rock Specimens Preparation.* Granite is an acidic ($SiO_2 > 66\%$) magmatic rock and is the most common kind of magmatic rock; it is generally light red, light gray, or gray. The main mineral components are quartz, potassium feldspar, and acidic plagioclase, and the secondary mineral components are biotite, hornblende, and sometimes a small amount of pyroxene. There are many accessory minerals, including magnetite, sphene, zircon, apatite, tourmaline, and fluorite. The quartz content in granite is the largest among all kinds of magmatic rocks, and its content generally ranges from 20 to 50% but can reach 50 to 60%. The content of potassium feldspar is generally more than that of plagioclase, potassium feldspar often accounts for two-thirds of the total feldspar, and plagioclase often accounts for one-third. The potassium feldspar in granite is mostly light red, gray-white, or gray.

The rock material selected in this test is fine-grained granite with an average density of 2810 kg/m$^3$. The diameter of the specimen is 10 times larger than that of the any particle, which meets the test requirements. The ends of the specimens have the corresponding specifications after coring, cutting, and grinding, specimen plane parallel and a series of processes comply with the the requirements specimen plane parallel ≤ ±0.3 mm or less, deviation ≤ ±0.25° transverse to the vertical axis of the specimens. The granite specimens are 50 mm in diameter and they have length-diameter ratios of 0.5, 0.6, 0.7, 0.8, 0.9, and 1.0, corresponding to lengths of 25 mm, 30 mm, 45 mm, and 50 mm. Each granite specimen type is triplicated.

*2.2. Experimental Method.* The static loading test system is an RMT-150B rock mechanics servo control system. The displacement control loading method is adopted in the test, and the loading rate is 0.002 mm/s. A pressure sensor of 1000 kN is adopted in the vertical direction. The dynamic impact test equipment is an SHPB that adopts a combined dynamic and static loading system. The incident bar, transmission bar, and absorption bar are made of 40 Cr alloy steel, and the granite specimen is compressed dynamically. The quasistatic and dynamic loading devices are shown in Figure 1.

The RMT equipment was used to load the specimens in the quasistatic test; the compressive strength of each specimen length was obtained, and the average value of the data was obtained. The SPHB equipment was used to load the specimens in the dynamic tests. Before failure, both ends of the rock specimen were in a state of equilibrium, and the stress distribution was uniform. The stress deviation after failure did not affect the reliability of the test results. The impact pressure was 1 MPa. According to the stress wave signals collected by the strain gauges on the incident bar and transmission bar, based on one-dimensional stress wave theory and the assumption of stress uniformity, the three-wave formula, whose calculation principle is shown in equation (1), is used to calculate the stress and average strain rate of the specimen during the impact process. The quasistatic and dynamic compressive strengths are shown in Table 1.

$$\left.\begin{aligned} \sigma_s &= \frac{A_B E}{2A_S}\left[\varepsilon_t(t) + \varepsilon_r(t) + \varepsilon_i(t)\right] \\ \dot{\varepsilon}(t) &= \frac{C}{L}\left[\varepsilon_t(t) + \varepsilon_r(t) - \varepsilon_i(t)\right] \\ \varepsilon_t(t) &= \frac{C}{L}\int_0^t \left[\varepsilon_t(t) + \varepsilon_r(t) - \varepsilon_i(t)\right]\mathrm{d}t \end{aligned}\right\}, \qquad (1)$$

where $A_B$, $E$, and $C$ are the cross-sectional area of the bar, the elastic modulus, and the wave velocity of the elastic compression wave, respectively. $A_S$ and $L$ are the cross-sectional area and length of the specimen, respectively. $\varepsilon_i(t)$, $\varepsilon_r(t)$, $\varepsilon_t(t)$ are the strains of the incident wave, reflected wave, and transmitted wave of the pressure bar at time $t$, respectively.

## 3. Quasistatic Experiment Failure and Analysis

*3.1. Quasistatic Experiment Failure Characteristics.* The test material is fine-grained granite. Uniaxial compression is carried out on specimens of different sizes. The specimen strength decreasing with increasing specimen length has an obvious size effect. The uniaxial compression test results show that the failure modes of the specimens are complex and are closely related to the physical and mechanical properties of the specimens and the test conditions. The end effect has a great influence on the failure mode of the specimens and can change the failure mode. The failure modes of granite specimens with different length-diameter ratios in uniaxial compression tests are shown in Figure 2.

When the size of specimen is smaller, there are fewer micro defects inside the rock, the uniformity is better, the strength is higher, the friction between the specimen end and the pressure head of the testing machine is isotropic, and more of the material reaches the yield weakening point. The failure modes of specimens with different length-diameter ratios are complex. The granite specimens with lengths of 25 mm, 30 mm, 35 mm, and 40 mm exhibited many fracture surfaces along the axial direction. Rock specimens with 45 mm and 50 mm in length exhibited stripping, resulting in shear failure, and the failure mode is conical [22]. In the uniaxial compression test, the stiffness between the testing machine and the rock sample is not the same, friction occurs between the end of the testing machine and the end of rock specimens, and the friction effect caused by the end face of the specimen in contact with the testing machine had a great influence on the failure mode of the specimen. Because the friction between the specimen end faces and the machine head changed the stress state of the end of the specimen and a triangular pattern of compressive stress near the top and bottom ends and tensile stress elsewhere, the sides of the specimen underwent outward deformation and stripping in unconfined condition, eventually resulting in conical failure. With the increase in the height-diameter ratio, the stress distribution around the specimen is caused by the friction between the end face of the specimen and the pressure head of the testing machine [15]. With the decrease in the specimen height-diameter ratio, the influence of the compressive stress area of the triangular pattern increases, thus complicating the damage form of the specimens. However, with the increase in the length-diameter ratio, its influence gradually weakened.

*3.2. Quasistatic Experiment Failure Results.* As shown in Figure 3, granite compressive strength has an obvious size effect. The compressive strength of the 25 mm specimen is 140.02 MPa, and, with increasing length, the granite compressive strength decreases significantly. The compressive strength of the 50 mm specimen drops to 124.924 MPa,

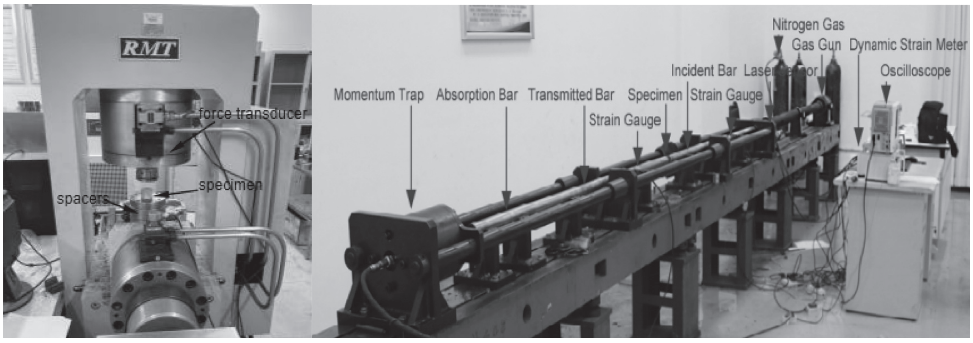


Figure 1: Quasistatic and dynamic experimental devices.

Table 1: Quasistatic and dynamic experiment testing.

| Length (mm) | Quasistatic loading rate (mm/s) | Quasistatic compression strength $\sigma$ (MPa) | Air pressure (MPa) | Dynamic loading strain rate (S) | Dynamic compression strength $\sigma$ (MPa) |
|---|---|---|---|---|---|
| 25 | | 140.02 | | 184.648 | 407.925 |
| 30 | | 135.699 | | 147.866 | 415.975 |
| 35 | 0.002 | 133.046 | 1 | 128.547 | 422.273 |
| 40 | | 130.977 | | 111.081 | 401.27 |
| 45 | | 128.056 | | 100.865 | 420.875 |
| 50 | | 124.924 | | 88.864 | 410.903 |

(a) (b) (c) (d) (e) (f)

Figure 2: Quasistatic loading state of granite with different length-diameter ratios. (a) $L = 25$ mm. (b) $L = 30$ mm. (c) $L = 35$ mm. (d) $L = 40$ mm. (e) $L = 45$ mm. (f) $L = 50$ mm.

which is consistent with the general rule of the size effect. Granite is generally considered a heterogeneous material, and the smaller the size of the specimen is, the lower the probability of internal defects is and the higher the strength of the specimen is. Combined with the nonnegligible friction effect of uniaxial compression in the failure pattern (Figure 2) of the specimen, the failure of the specimens with length-diameter ratios of 0.5~0.8 is axial splitting, which indicates that these specimens have greater compressive strength under high three-dimensional stress state. The larger the length-diameter ratio of the specimen is, the closer the stress distribution to that of a one-dimensional stress is. For granite specimens with length-diameter ratios of 0.9 and 1.0, a conical failure pattern appears. In the middle part of the specimen, there is a one-dimensional stress state, and the compressive strength is lower than that of the zone with a three-dimensional stress state. With the increase in the length-diameter ratio of the specimens, the compressive strength of the rock material decreases, and the friction effect at the end and the superposition of internal defects in the rock material are the reason for the decrease in its compressive strength.

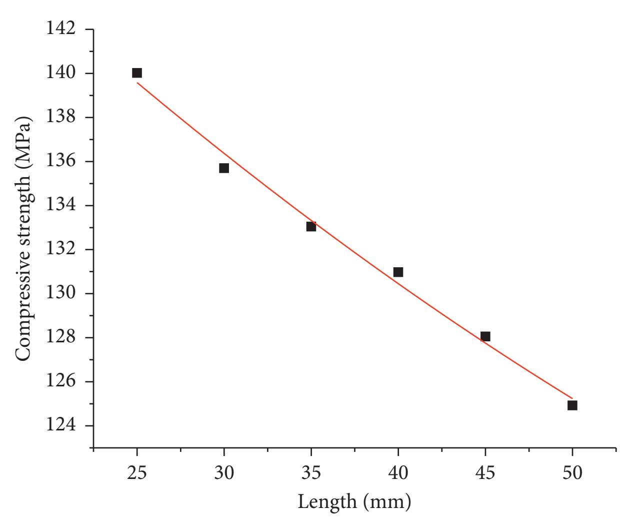


Figure 3: Relationship between length ratios and compressive strength.

*3.3. Theoretical Analysis of the Size Effect of Granite under Quasistatic Conditions.* Most static fracture analyses of brittle and quasibrittle materials are based on the weakest link model, and the Weibull distribution is widely used in the study of the size effect of the compressive strength of brittle and quasibrittle materials. The distribution function and probability density function of the three-parameter Weibull distribution are as follows:

$$f(\sigma) = \frac{m}{\sigma_0}\left\langle \frac{\sigma - \sigma_u}{\sigma_0} \right\rangle^{m-1} \exp\left( -\left\langle \frac{\sigma - \sigma_u}{\sigma_0} \right\rangle^{m} \right),$$
$$F(\sigma) = 1 - \exp\left( -\left\langle \frac{\sigma - \sigma_u}{\sigma_0} \right\rangle^{m} \right), \tag{2}$$

where  are McCaulay brackets, $\sigma$ is the peak strength, $\sigma_0$ is the scale parameter, and $\sigma_u$ is the lowest of $\sigma$, where $\sigma_u \leq \sigma \leq \infty$; and $m$ is the homogeneity of the material, where $m > 1$.

The strength of granite at instability failure can be approximately expressed by the three-parameter Weibull distribution, and its probability density function and failure probability are as follows [16]:

$$p(\sigma) = \frac{V}{V_0}\left\langle \frac{\sigma - \sigma_u}{\sigma_0} \right\rangle^{m} \exp\left( -\frac{V}{V_0}\left\langle \frac{\sigma - \sigma_u}{\sigma_0} \right\rangle^{m} \right),$$
$$P(\sigma) = 1 - \exp\left( -\frac{V}{V_0}\left\langle \frac{\sigma - \sigma_u}{\sigma_0} \right\rangle^{m} \right), \tag{3}$$

where $V$ is the volume of the specimen; $V_0$ is the reference volume.

For the convenience of calculation [5], by assuming $\sigma_u = 0$ and considering the case of only two parameters, the probability density and failure probability of granite instability failure are

$$p(\sigma) = \frac{V}{V_0}\left\langle \frac{\sigma}{\sigma_0} \right\rangle^{m} \exp\left( -\frac{V}{V_0}\left\langle \frac{\sigma}{\sigma_0} \right\rangle^{m} \right), \tag{4}$$

$$P(\sigma) = 1 - \exp\left( -\frac{V}{V_0}\left\langle \frac{\sigma}{\sigma_0} \right\rangle^{m} \right), \quad (\sigma \geq 0). \tag{5}$$

Average strength at rock failure is

$$\overline{\sigma} = \int_{-\infty}^{\infty} \sigma \mathrm{d}P(\sigma). \tag{6}$$

Substitute equation (5) into equation (6) to obtain the average strength of the tested granite at failure:

$$\overline{\sigma} = \sigma_0 \left( \frac{V}{V_0} \right)^{-(1/m)} \Gamma\left( \frac{1+1}{m} \right), \tag{7}$$

where $\Gamma$ represents the gamma function.

The specimens with a uniform diameter of 50 mm were selected for the experiment, so $V_0/V = L_0/L$. Equation (7) can be rewritten as follows:

$$\overline{\sigma} = \sigma_0 \left( \frac{L_0}{L} \right)^{(1/m)} \Gamma\left( \frac{1+1}{m} \right). \tag{8}$$

Taking $L_0 = 25$ mm, the actual compressive strength of the corresponding size specimen is $\sigma_0 = 140.02$ MPa. According to the test results of the specimen, $m$ was determined to be 5.7, and the average strength of the granite specimens of each length was obtained with equation (8). For this experimental scale, equation (8) can be simplified into

$$\overline{\sigma} = 227.812L^{-0.1754}. \tag{9}$$

The comparison between the compressive strength under quasistatic loading calculated by equation (9) and the test compressive strength is shown in Table 2. The difference between the calculated rock compressive strength and the actual experimental compressive strength is small. The difference between the calculated rock compressive strength and the actual experimental compressive strength is the largest for the specimen with a length of 40 mm, the corresponding result is 9.923 MPa, and the error rate is 7.123%.

Figure 4 reflects the calculated average compressive strength and actual compressive strength; the relationship between the actual compressive strength of the specimens with the length of 25 mm at scale parameter $\sigma_0$ and that of the specimens with the other lengths shows that the calculated average compressive strength is slightly less than the actual compressive strength, which is consistent with the size effect of compressive strength. In the quasistatic experiment, the specimen strength decreases with the increase in the specimen length, with type 10 showing the size effect of granite compressive strength under quasistatic conditions.

## 4. Dynamic Experiment Failure and Analysis

*4.1. Dynamic Experiment Failure Characteristics.* The high-speed photography of the rock failure process (Figure 5) shows that the impact damage did not happen in front and back units of the specimen face. Instead, a crack first appeared in the side of the specimen, and, with the passage of time, debris ejected from the specimen, which split along the axial surface, forming numerous fragments. The main failure mode of these specimens was tensile fracture along the axial direction. This is because the specimen is in a one-dimensional compression state during compression. The side of the specimen is a free surface, and the compression wave is reflected into a tensile wave. Because the tensile strength is low, the deformation easily leads to tensile failure for rock-like materials with low compressive strength.

Under the condition of an impact pressure of 1 MPa, after the specimens were impacted by the incident bar, the rock exhibited a fracture surface. Because the rock specimens between the incident bar and the transmission bar repeatedly were impacted, numerous small fragments were formed. After the impact, some of the surface fragments were ejected. Figure 6 shows that the specimen with a length of 25 mm became almost powdery, and most of the fragments are of the order of several millimeters. Characteristic fragment sizes of the specimens with lengths of 30 mm, 35 mm, 40 mm, 45 mm, and 50 mm are several centimeters.

Table 2: Experimental and mean compressive strength of quasistatic loading.

| Length (mm) | Experimental compressive strength $\sigma$ (MPa) | Mean compressive strength $\overline{\sigma}$ (MPa) | Error rate (%) |
|---|---|---|---|
| 25 | 140.02 | 140.02 | - |
| 30 | 135.699 | 127.946 | 5.713 |
| 35 | 133.046 | 124.522 | 6.407 |
| 40 | 130.977 | 121.648 | 7.123 |
| 45 | 128.056 | 119.16 | 6.95 |
| 50 | 124.924 | 116.978 | 6.361 |

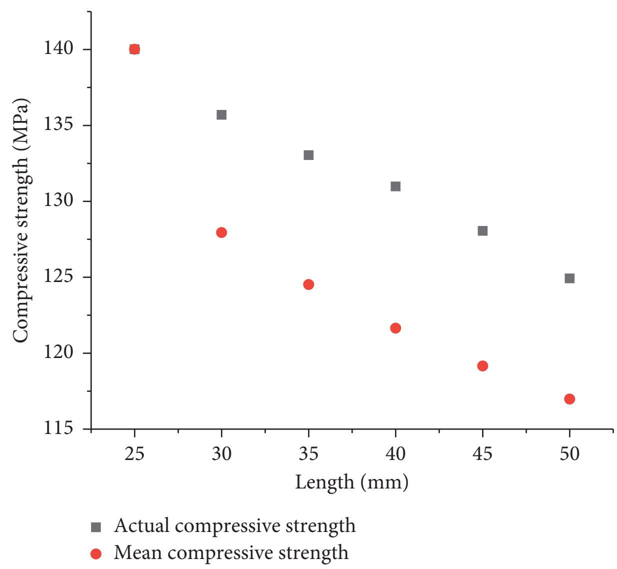


Figure 4: Relationship between lengths with actual compressive strength and mean compressive strength.

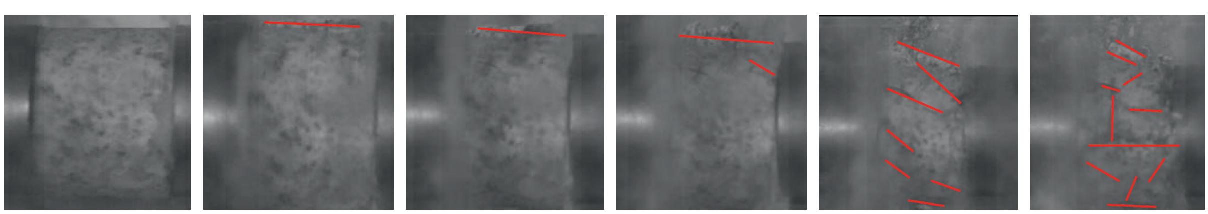

Figure 5: Granite specimen impact process.

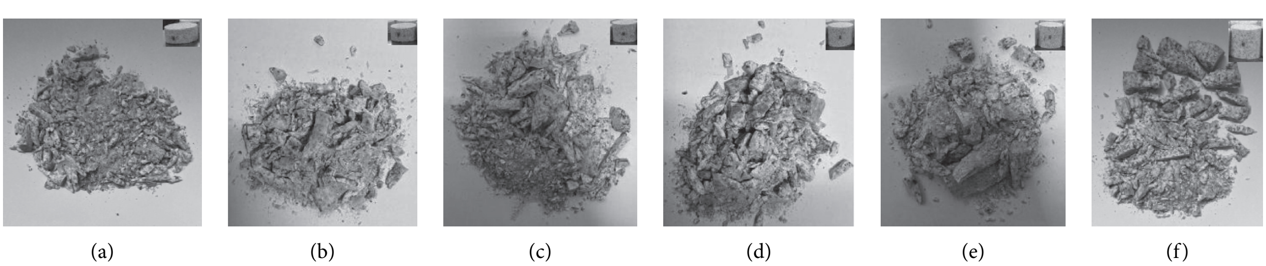


Figure 6: Granite specimens with length-diameter ratios of 0.5~1 were broken. (a) $L = 25$ mm. (b) $L = 30$ mm. (c) $L = 35$ mm. (d) $L = 40$ mm. (e) $L = 45$ mm. (f) $L = 50$ mm.

The sizes of the fragments of short specimens are more uniform, and the proportion of large fragments is lower than long specimens.

*4.2. Failure Results of the Dynamic Experiment.* The compressive strength of the 25 mm specimen is 407.925 MPa, the maximum compressive strength of the 50 mm specimen is 410.903 MPa, and the minimum compressive strength of the 40 mm specimen is 401.27 MPa. The relationship between the compressive strength and size is not obvious. Hong et al. [23] used SHPB to load granite specimens of different sizes and concluded that the higher the strain rate of rocks of the same size is, the higher the strength is. Meanwhile, the higher the strain rate is, the more significant influence of the specimen size change on the strength is. Jin et al. [24, 25] studied the compressive strength of rocks of different sizes under the same strain rate. The compressive strength increased with increasing size, and there is a complicated relationship between the specimen size and strain rates.

The explanation and application of the dynamic size effect are still unclear. At high strain rates, the contribution of the inertia effect to the dynamic compressive strength enhancement is significantly increased and dominant. The larger the size is, the stronger the inertia force is. At the same time, the lateral constraining effect is greatly enhanced, and the horizontal inertia force generated caused the granite specimen to be in a highly complex triaxial stress state, which makes the dynamic compressive strength correspond to a size effect rule that is inconsistent with that of the quasistatic compressive strength. The relationship between the length and the dynamic compressive strength in Figure 7 shows that, under an impact pressure of 1 MPa, the compressive strength and size of specimens with the same diameter are weakly correlated. The size effect and strain rate effect are coupled; under impact loading, different specimen sizes can lead to changes in the strain rate and other factors that influence the specimen compressive strength; at the same time, the compressive strength is very sensitive to changes caused by the strain rate, so analyses of dynamic compressive strength and the influence factor of strain rate and size must be considered.

*4.3. Theoretical Analysis of the Size Effect of Granite under Dynamic Conditions.* Under dynamic loading, not only the size effect characteristics but also the inherent strain rate effect of materials is considered. The size effect dynamic compressive strength presents a "weakened the reverse strengthening first" trend with the increase in the strain rate [26], so the critical strain rate is when the strain rate is less than the critical value, the influence of specimen size on compressive strength is important, and the compressive strength only slightly changes with the increase in the strain rate; and when the strain rate is more than the critical value, the influence of specimen strain rate on compressive strength is important, and the compressive strength greatly changes with the increase in the strain rate. Olsson [27] calculated that the critical strain rate was 76 $s^{-1}$ by correcting the relationship between strength and strain rate of average density, considering change in the porosity of rock specimens. Wang et al. [19] studied 101 specimens that conformed to the stress wave equilibrium theory of quasibrittle materials and determined that the relevant parameter of the strain rate effect was 3.24.

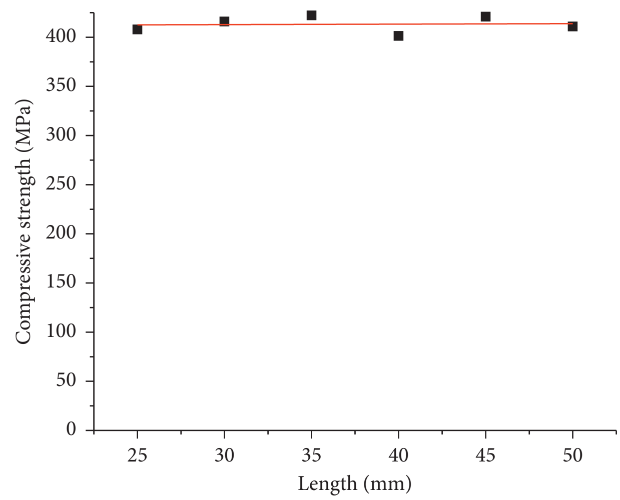


Figure 7: Relationship between length ratios and compressive strength.

Considering the influence of the strain rate and size, the failure probability density function and failure probability of granite can be expressed as follows [19]:

$$p(\sigma) = \left(\frac{V}{V_0}\right)^{\alpha \ln (\dot{\varepsilon}_0/\dot{\varepsilon})} \frac{m}{\sigma_1}\left(\frac{\sigma}{\sigma_1}\right)^{(m-1)} \cdot \exp\left[-\left(\frac{V}{V_0}\right)^{\alpha \ln (\dot{\varepsilon}_0/\dot{\varepsilon})}\left(\frac{\sigma}{\sigma_1}\right)^{m}\right], \tag{10}$$

$$P(\sigma) = 1 - \exp\left[-\left(\frac{V}{V_0}\right)^{\alpha \ln (\dot{\varepsilon}_0/\dot{\varepsilon})}\left(\frac{\sigma}{\sigma_1}\right)^{m}\right]. \tag{11}$$

$\dot{\varepsilon}$ is the strain rate, $\dot{\varepsilon}_0$ is the critical strain rate [27], $\alpha$ is the rate effect related parameter, and $\sigma_1$ is the dynamic scale parameter.

Substitute equation (11) into equation (6) to obtain the average compressive strength at granite specimens failure:

$$\overline{\sigma} = \sigma_1\left(\frac{V}{V_0}\right)^{(\alpha/m)\ln (\dot{\varepsilon}_0/\dot{\varepsilon})} \Gamma\left(\frac{1+1}{m}\right). \tag{12}$$

Granite specimens with a uniform diameter of 50 mm were selected for the experiment, so $V_0/V = L_0/L$.

Equation (12) can be rewritten as follows:

$$\overline{\sigma} = \sigma_1\left(\frac{L}{L_0}\right)^{(\alpha/m)\ln (\dot{\varepsilon}_0/\dot{\varepsilon})} \Gamma\left(\frac{1+1}{m}\right). \tag{13}$$

When $\sigma_1$ is $L_0 = 25$ mm, the actual dynamic compressive strength of the test is 407.925 MPa.

Within the test scale, equation (13) can be simplified:

$$\overline{\sigma} = 377.371\,(0.04L)^{0.568 \ln (\dot{\varepsilon}/76)}. \tag{14}$$

A comparison between the experimental compressive strength under dynamic loading and the average compressive

Table 3: Experimental and mean compressive strength of dynamic loading.

| Length (mm) | Strain rate (S) | Experimental compressive strength $\sigma$(MPa) | Mean compression strength $\overline{\sigma}$(MPa) | Error rate (%) |
|---|---|---|---|---|
| 25 | 184.648 | 407.925 | 407.925 | - |
| 30 | 147.866 | 415.975 | 404.369 | 2.79 |
| 35 | 128.547 | 422.273 | 417.318 | 1.173 |
| 40 | 111.081 | 401.27 | 417.686 | 4.091 |
| 45 | 100.865 | 420.875 | 414.847 | 1.432 |
| 50 | 88.864 | 410.903 | 401.407 | 2.311 |

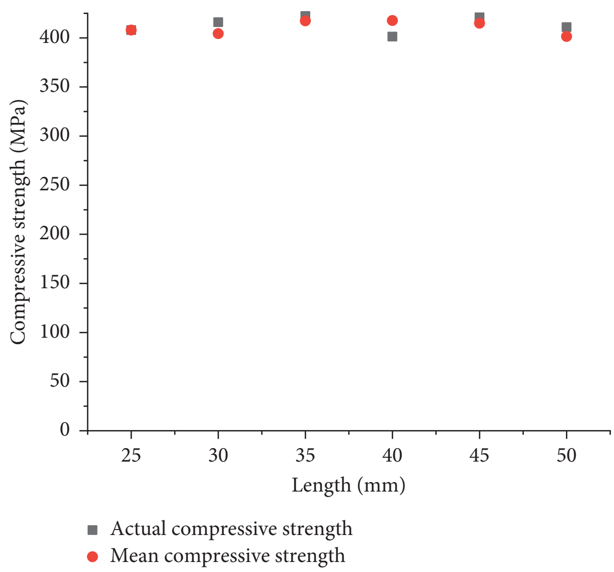


Figure 8: Relationship between lengths with actual compressive strength and mean compressive strength.

strength calculated by equation (14) is shown in Table 3. The difference between the calculated average compressive strength of specimens and the actual compressive strength is low. The maximum difference between the average compressive strength of specimens with a length of 40 mm and the actual compressive strength is 16.416 MPa, and the error rate is 4.091%.

Figure 8 reflects the actual compressive strength and average compressive strength results. The actual compressive strength of the 25 mm specimen was taken as the scale parameter $\sigma_1$, and the average compressive strength of specimens calculated is consistent with the actual rule of the compressive strength; under dynamic loading, specimen size and strain rate parameters (type 15) can effectively draw the dynamic rock strength size effect rule.

## 5. Conclusion

Quasistatic and dynamic uniaxial compression experiments were carried out on granite specimens with length-diameter ratios of 0.5~1. Failure modes and strength size effects of specimens with different sizes were studied. The results were confirmed by Weibull analysis and error analysis, and the following conclusions were drawn:

(1) Under the quasistatic loading condition, the failure form of specimens with lengths of 25 mm, 30 mm, 35 mm, and 40 mm was axial splitting, and the failure form of specimens with lengths of 45 mm and 50 mm was conical stripping. When the specimen size is larger, the probability of defects is greater, the failure is affected by the friction effect, and the rock strength decreases with increasing size.

(2) Based on the Weibull distribution function, a volume parameter is introduced, and the relationship between the specimen strength and size is intuitively expressed by the improved quasistatic Weibull formula, which can well calculate the rock strength of different sizes. With increasing specimen volume, the failure probability increases monotonically, and the strength decreases monotonically.

(3) Under the dynamic loading condition, at the beginning of loading, cracks appeared on the side of the specimen, which led to penetration through the specimen, causing rapid fracture of the specimen and ejection of some large fragments, most of which were on the order of millimeters in size. Under the dynamic impact condition, the rock strength change is due to some complex mechanism, and the compressive strength of rock is weakly correlated with the size.

(4) Considering the strain rate effect, on the basis of the improved Weibull formula, the dynamic compressive strength of specimens of different sizes was accurately calculated by introducing relevant parameters. Based on the Weibull function, the relationship between the material strength and the specimen size was further expounded under the unified theoretical framework of quasistatic and dynamic loading.

## Data Availability

The data used to support the findings of this study have not been made available because the experimental data involved in the paper are all obtained based on the authors' designed experiments and need to be kept confidential; they are still using the data for further research.

## Conflicts of Interest

The authors declare that they have no conflicts of interest.


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