Research Article

Research on the Conversion Relationship between Dynamic Point Load Strength and Dynamic Compressive Strength Based on Energy System

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Point load test is a simple and fast method to obtain the compressive strength of rock. According to the maximum load at failure and the distance between two cone ends, the compressive strength of specimens can be calculated by the empirical formula. Because the test process does not need to process the sample into laboratory size type, so it is widely used. At the same time, with the rapid development of rock dynamics, the dynamic strength index of rock becomes more and more important under dynamic load. But dynamic point load is seldom mentioned by scholars. In order to explore the correlation between dynamic point load test and dynamic compressive strength, a large number of dynamic point load and uniaxial dynamic compressive strength tests were carried out using a split Hopkinson pressure bar for granite. Based on the energy theory, the crushing energy consumption during dynamic point load and uniaxial dynamic compressive strength tests were statistically analyzed, and the transformational relation between uniaxial dynamic compressive strength and crushing energy consumption during the dynamic point load test was determined. At the same time, the influence of the cone angle on crushing energy consumption during the dynamic point load test was investigated by changing the conical angle. The results show that with the increase in conical angle, the energy consumption of rock crushing decreases gradually during the dynamic point load test. And the decreasing trend tends to be gentle. The conclusion can provide a reference for obtaining the numerical value of the dynamic compressive strength of the rock in the future.

1. Introduction

Point load test is a simple method to test the compressive strength of rock, concrete, or other natural building materials under point load. Scholars at home and abroad have also made many research achievements on point load test. Koncagül and Santi [1] first proposed the idea of using irregular blocks to carry out point load test. Later, in 1972, the Committee of the International Society for Rock Mechanics recommended the use of the rock point load strength test method, and in 1985, it proposed a revised method to calculate the uniaxial compressive strength of rock, which has been widely recognized by most scholars [2]. Since then, in terms of point loads, a large number of scholars have studied it from different angles and different lithologies, including the relationship between point load strength and uniaxial compressive strength [3–9] and the determination of correction coefficient [10–14]. For example, D’Andrea et al. [15] were the first to indirectly estimate the uniaxial compressive strength of rock through a linear relationship, pointing out the linear correlation between point load strength index and uniaxial compressive strength. Franklin [2] found that the results of the unconfined uniaxial compressive strength test were closely related to the results of point load strength test, and the dispersion of the radial point load test was small. They described the development of a portable testing machine and suggested a conversion coefficient of 24. Bieniawski [16] evaluated the strength changes of three loading methods (axial test, radial test, and irregular test), found that the radial point load test was the
most convenient to use, established the relationship between the three uniaxial compressive strength and point load index, and compiled a simple dimensional correlation diagram. All these proved the importance of point load-related research. The above studies were only for static point load test and static uniaxial compressive strength. However, with the rapid development of rock dynamics, dynamic load engineering problems such as deep mining, high slope blasting, and long tunnel (cave) excavation occurred, and dynamic compressive strength plays an important role in application [5, 17–20]. Therefore, it is of great significance to study whether the corresponding dynamic compressive strength can be determined through the dynamic point load test and how the transformation relationship between them. In terms of crack initiation and propagation, Haeri et al. [21] studied the fundamental failures occurring in a rock bridge. At the same time, the crack initiation, propagation, and rupture process of the CSCBD specimen under diameter compression were analyzed, tested, and simulated numerically. [22] Sarfarazi et al. [23] used the PFC2D method to study the influence of joint separation on the shear behavior of nonpersistent planar joints under high normal loads. And they compared stress-strain model prediction and test results for marble, sandstone, and dense Cambrian. The comparison showed that the model can accurately reproduce the mechanical behavior of rock. [24] In terms of impact research, Kumar [25] first applied the SHPB device to the test of rock dynamic strength in 1968. Bunshah [26] obtained the dynamic compression stress-strain curves of many metal materials in the range of strain rate 102 s−1–103 s−1 through a large number of tests. Zhou et al. [27] found that the dynamic compressive strength increases first, then decreases slowly, and at last drops rapidly with the increase in prestress and found that for each water content, the dynamic tensile strength of sandstone is positively sensitive to loading rate by dynamic Brazilian disc experiments [28]. Janach [29] conducted impact tests on limestone and granite using the SHPB test facility, and the results also showed that the two kinds of rock dynamic strength are much higher than the static uniaxial compressive strength. These studies [30–36] promoted the focus of point load research from static mechanics to dynamic mechanics test and provided ideas for the transformation from static point load test to dynamic point load test in this paper. In terms of the improvement of impact device, Chang [37] proposed the formula of penetration depth by using a simplified impact model, mechanics principle, and Bayesian statistical analysis of test data. Haldar and Hamieh [38] proposed an expression for the estimation of penetration depth based on data collection and analysis. The above research [39–42] provides thought support for the modification of the impact rod end of the SHPB impact device.

To sum up, there were only studies on static tests to calculate the compressive strength by using point load strength, and there were few studies on whether the dynamic compressive strength can be converted by point load test. In the Hopkinson impact experiment, there are few precedents of conical contact impact. This paper takes granite as the research object, carries out a dynamic impact compression test and dynamic point load test with a split Hopkinson pressure bar, and analyzes the crushing energy consumption in the two tests, respectively. Since the dynamic point load test cannot accurately calculate the strain rate, impact velocity is used as the medium. The relationship between impact velocity and crushing energy consumption in the impact compression test and that between impact velocity and dynamic point load test were fitted. Then, the proportion of crushing energy consumption in the dynamic point load test and dynamic compression test is determined. At the same time, the influence of different punch shapes on crushing energy consumption during the dynamic point load test was discussed by changing the cone angle of impact bar ends. Finally, the conversion relationship between the dynamic point load test crushing energy consumption and dynamic compression test crushing energy consumption under different conditions (different conical angles) was obtained by fitting.

2. Test Plan

2.1. Instrument and Method of Use. The dynamic uniaxial compression test adopts a split Hopkinson pressure bar (as shown in Figure 1). The diameter of the pressure bar is 50 mm, its elastic modulus E is 210 GPa, density is 7787 kg/m³, wave velocity is 5667 m/s, the bullet is a spindle bullet of 0.26 m, and the length of the steel bar is 1.5 m. When testing, pay attention to the following experimental operation details: Both ends of the sample are fully coupled with grease to avoid mass reflection or consumption at the end due to insufficient transport medium. After the test began, the impact pressure was controlled to control the impact velocity, and the waveform of the incident, reflection, and transmission was collected by ultradynamic acquisition instrument.

The dynamic point load test is conducted by adding a self-designed point load impact rod head at one end of the incident bar (as shown in Figure 2). During the test, one end of the transmission bar was covered with a protective sleeve to prevent the impact rod head from continuing to damage the transmission bar after the sample was broken under the condition of a high strain rate. At the same time, the inside of the impact bar and the protection bar is coupled with the corresponding rod through grease. At the end of the test, the impact velocity was recorded, and the fragments and debris of the crushed sample were collected.

2.2. Preparation of Samples. The rock samples used in the test were all taken from the same large mine. In order to reduce the influence of nonuniformity on the test results, all samples in the test were cut from a complete granite block without obvious cracks. In the process of machining, the whole rock sample was cut into 32 standard patterns, which were divided into two groups for the dynamic point load test and impact compression test, respectively. Part of the sample is shown in Figure 3.
3. Test Results and Analysis

3.1. Data Processing

3.1.1. Acquisition of Crushing Energy Consumption for Dynamic Uniaxial Compressive Strength Test. Figure 4 shows the schematic diagram of the SHPB impact compression test. According to the above one-dimensional elastic wave hypothesis and stress-strain uniformity hypothesis, the stress \( \sigma_i(t) \), strain rate \( \dot{\varepsilon}_i(t) \), and strain \( \varepsilon_i(t) \) of the sample are as follows:

\[
\sigma_i(t) = \frac{EA_0}{2A_s} \left[ \dot{\varepsilon}_i(t) + \varepsilon_i(t) + \varepsilon_i(t) \right],
\]

\[
\dot{\varepsilon}_i(t) = \frac{C_0}{l_s} \left[ \varepsilon_i(t) - \varepsilon_i(t) - \varepsilon_i(t) \right],
\]

\[
\varepsilon_i(t) = \frac{C_0}{l_s} \int_0^t \left[ \varepsilon_i(t) - \varepsilon_i(t) - \varepsilon_i(t) \right] \, dt,
\]

\[
W_i = \frac{A_0C_0}{E} \int_0^t \sigma_i^2 \, dt = A_0C_0E \int_0^t \dot{\varepsilon}_i^2 \, dt,
\]

\[
W_r = \frac{A_0C_0}{E} \int_0^t \sigma_r^2 \, dt = A_0C_0E \int_0^t \dot{\varepsilon}_r^2 \, dt,
\]

\[
W_t = \frac{A_0C_0}{E} \int_0^t \sigma_t^2 \, dt = A_0C_0E \int_0^t \dot{\varepsilon}_t^2 \, dt,
\]

\[
W_a = W_i - W_r - W_t,
\]

where \( A_s \) is the cross-sectional area of the test block; \( l_s \) is the initial length of the test bar; \( A_0 \) is the cross-sectional area of the bar; \( C_0 \) is the propagation velocity of stress wave in the bar; \( E \) is the elastic modulus of the pressure bar; \( \sigma_i, \dot{\varepsilon}_i \) is the stress and strain of the incident bar; \( \sigma_r, \dot{\varepsilon}_r \) is the stress and strain of the reflecting bar; \( \sigma_t, \dot{\varepsilon}_t \) is the stress and strain of the transmission bar; \( W_i \) is the incident energy; \( W_r \) is the reflection energy; \( W_t \) is the transmission energy; and \( W_a \) is the energy consumption of the broken.

Figure 5 shows the signal of the half-sine stress wave in a typical sample test. The three-wave method is used to verify the stress balance state during data processing. When the superposition curves of the incident and reflected waves and transmitted waves change from coincidence to coincidence and then to coincidence, it can be considered that the sample is in a state of stress balance in the process of dynamic loading.

The uniaxial impact compression experiment of typical granite was carried out by the SHPB system. The data are shown in Table 1. The crushing forms and stress-strain curves of granite under the SHPB experimental system are shown in Figures 6 and 7, respectively.

It can be seen from Figures 6 and 7 that the crushing scale and dynamic elastic modulus and peak stress of granite all show obvious strain rate effect. With the increase in strain rate, the crushing size decreases, and the dynamic elastic modulus and peak stress all show an increasing trend with the increase in strain rate. The rock has a strain rate effect, and the dynamic mechanical strength of intact granite samples is different under different strain rates. The dynamic compressive strength of rock increases with the increase in strain rate and impact velocity. For granite, when the stress reaches the yield stress, the stress-strain curve enters a significant plastic deformation stage with the increase in strain, and there is only a small plastic deformation stage before and after the peak stress. Microscopically, this phenomenon corresponds to a series of stages of the adiabatic shear process. The dynamic stress-strain relationship of rock with complex morphology is actually a comprehensive reflection of the strain hardening effect, strain rate strengthening effect, and thermal softening effect caused by adiabatic temperature rise.

In this paper, \( W_a \) is used to represent the crushing energy consumption in the impact compression test, \( W_a^{(60°)} \) represents the crushing energy consumption in the point load test, where (60°) represents that the conical angle selected in the point load test is 60°. The following figure shows the energy time-history curves of several groups of typical impact compression tests, as shown in Figure 8. As can be seen from the figure, with the increase in impact velocity, the incident energy of granite increases, and so does the crushing energy consumption. A second-order fitting was carried out between the crushing energy consumption of the sample and the corresponding impact velocity, as shown in Figure 9. The fitting formula is as follows:

\[
W_a = 5.08v^2 - 102.24v + 555.4, \quad \text{and the determination coefficient} \quad R^2 = 0.98, \quad \text{indicating a good fitting degree.}
\]

The crushing energy consumption of the impact compression test was fitted with the corresponding dynamic uniaxial compressive strength, as shown in Figure 10. The fitting formula is \( W_a = 1.176\sigma - 113.694 \), and the determination coefficient \( R^2 \) is 0.89.

3.1.2. Energy Consumption of Crushing for Dynamic Point Load Test. When the SHPB device is used for the test, the \( \sigma - \varepsilon - \dot{\varepsilon} \) relationship of the sample needs to meet certain assumptions. For example, the whole system should be in a
Figure 3: Test sample.

Figure 4: Schematic diagram of SHPB impact compression test loading.

Figure 5: Electrical signal diagram of the typical sample during the experiment.

Table 1: Uniaxial impact compression test data.

<table>
<thead>
<tr>
<th>Sample number</th>
<th>V/m · s⁻¹</th>
<th>W_1/J</th>
<th>σ/MPa</th>
<th>W_2/J</th>
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<tr>
<td>1</td>
<td>9.78</td>
<td>94.82</td>
<td>129.33</td>
<td>41.65</td>
</tr>
<tr>
<td>2</td>
<td>10.32</td>
<td>95.01</td>
<td>132.03</td>
<td>41.7</td>
</tr>
<tr>
<td>3</td>
<td>10.79</td>
<td>95.27</td>
<td>137.43</td>
<td>41.95</td>
</tr>
<tr>
<td>4</td>
<td>11.4</td>
<td>119.87</td>
<td>140.32</td>
<td>41.7</td>
</tr>
<tr>
<td>5</td>
<td>12.07</td>
<td>142.29</td>
<td>146.60</td>
<td>64.31</td>
</tr>
<tr>
<td>6</td>
<td>12.60</td>
<td>157.33</td>
<td>158.57</td>
<td>71.93</td>
</tr>
</tbody>
</table>

the relationship between the impact velocity and the energy consumption in the impact compression test (Figure 9) and the relationship between the impact velocity and the energy consumption in the dynamic load test (Figure 12) will be fitted again. Then, the relationship between energy consumption of impact compression test and dynamic load test is obtained, as shown in Figure 13, fitting formula is 

\[ W_a(60°) = 1.08W_a(60°) + 36.87 \]

and coefficient of determination \( R^2 \) is 0.9. Insert the fitting formula of \( W_a \) and dynamic compressive strength above into the formula to obtain 

\[ \sigma = 0.918W_a(60°) + 128.687 \]

In the formula, \( \sigma \) is the dynamic compressive strength, and \( W_a(60°) \) is the crushing energy consumption in the dynamic point load test.
Figure 6: Degree and form of breakage of granite under different strain rates: (a) 68.3 s\(^{-1}\), (b) 83.2 s\(^{-1}\), (c) 124.9 s\(^{-1}\), (d) 134.2 s\(^{-1}\), and (e) 142.5 s\(^{-1}\).

Figure 7: Dynamic compressive stress-strain curves of rock at different strain rates.

Figure 8: Continued.
3.1.3. Influence of Cone Angle on Crushing Energy Consumption during Dynamic Point Load Test. Two groups of dynamic point load impact tests were carried out by changing the cone angle to 90° and 120°. The relationship between impact velocity and crushing energy consumption in the experimental process was compared with that in the impact compression experiment. Figure 14 shows the fitting curves of dynamic point load crushing energy consumption and impact compression crushing energy consumption at three conical angles. As can be seen from the figure, when the cone angle is equal to 60° of the loading angle of the standard static point load test instrument, the crushing energy consumption of the dynamic point load test reaches maximum. With the...
FIGURE 10: Fitting curve of crushing energy consumption-dynamic compressive strength.

FIGURE 11: Energy time-history curve of the dynamic point load test at the conical angle of 60°. (a) Impact velocity 11.86 m/s. (b) Impact velocity 8.97 m/s. (c) Impact velocity 8.63 m/s. (d) Impact velocity 7.25 m/s.
Table 2: Test data of dynamic point load test at the conical angle of 60°.

<table>
<thead>
<tr>
<th>Sample number</th>
<th>$V/m \cdot s^{-1}$</th>
<th>$W_i/J$</th>
<th>$W_{a(60°)/J}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7.25</td>
<td>60.33</td>
<td>40.55</td>
</tr>
<tr>
<td>2</td>
<td>8.63</td>
<td>81.04</td>
<td>51.34</td>
</tr>
<tr>
<td>3</td>
<td>8.97</td>
<td>86.58</td>
<td>60.60</td>
</tr>
<tr>
<td>4</td>
<td>10.23</td>
<td>111.23</td>
<td>81.11</td>
</tr>
<tr>
<td>5</td>
<td>11.86</td>
<td>150.85</td>
<td>104.05</td>
</tr>
<tr>
<td>6</td>
<td>12.27</td>
<td>160.74</td>
<td>107.96</td>
</tr>
</tbody>
</table>

\[ W_{a(60°)} = 14.25v - 66.37 \]
\[ R^2 = 0.99 \]

Figure 12: Fitting curve of crushing energy consumption-impact velocity of dynamic point load test at conical angle of 60°.

\[ W_i = 1.08W_{a(60°)} + 36.87 \]
\[ R^2 = 0.93 \]

Figure 13: Fitting curve of crushing energy consumption of impact compression test-crushing energy consumption of dynamic point load test at conical angle of 60°.
increase in cone angle, the crushing energy consumption of the dynamic point load test gradually decreases, and the decrease trend tends to be gentle.

4. Conclusions and Future Work
The research results are as follows:

(i) In the impact compression test, the crushing scale, dynamic elastic modulus, and peak stress of granite all show an obvious strain rate effect. With the increase in strain rate, the crushing size decreases, and the dynamic elastic modulus and peak stress all show an increasing trend with the increase of strain rate.

(ii) There is a certain proportion between the crushing energy consumed in the impact compression test and that consumed in the dynamic point load test: $W_a = 1.08W_a(60\degree) + 36.87$. The relationship between uniaxial dynamic compressive strength and crushing energy consumption during the dynamic point load test is approximately as follows: $\sigma = 0.918W_a(60\degree) + 128.687$. It can provide a reference for obtaining the value of dynamic compressive strength of rock on site in the future.

(iii) When the dynamic point load test is carried out, the cone angle has an effect on the crushing energy consumed during the test. When the cone angle is greater than 60° of the loading angle of the standard static point load test instrument, the larger the cone angle, the smaller the crushing energy consumption in the test, and the decrease trend tends to be gentle.

Data Availability
Some or all data, models, or code generated or used during the study are available from the corresponding author by request.

Conflicts of Interest
The authors declare that they have no conflicts of interest.

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References


