Evaluation on Efficient Crushing Test in Deep Poor Drillability Formation

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Abstract. The ancient formation is very thick, strong abrasion and poor drillability. Formation pressure of some area is abnormal high-pressure, induced high mud density, and borehole instability problems in some formation restrict the positive displacement motor (PDM) application, and impact drilling tools are instable. All above factors restraint the rate of penetration. Based on the result of litho-mechanical experiments, the impacting experiments are performed on samples of the Jurassic formation, impact fractured efficiency are evaluated, the results show high impact resistance in the formation, the best impact speed is over 12m/s, and the result was important design basis for impact tools improvement to increase the rate of penetrate (ROP) in the deep poor drillability formation.

Keywords: Crushing test; Poor drillability; ROP.

1. Introduction
China is rich in deep oil and gas resources, but the penetration rate of deep well drilling is generally low. Taking Junggar Basin as an example, the average penetration rate of Jurassic formation is only 1.32 m/h, which seriously affects the drilling cycle and development benefit. Therefore, based on the analysis of the mechanical characteristics of the Jurassic formation in Junggar, the laboratory experiment was designed and carried out on the impact fracture of the formation with high efficiency this paper, some suggestions on the improvement of the speed-up tool for deep formation drilling was made, and a new idea for the speed-up of deep formation drilling was put forward (Wang Yilin P et.al, 2001).

2. Analysis of Rock Mechanical Properties
The lithology of Jurassic formation is mainly sandstone and mudstone, with a thickness of about 1500 m in the central block of Junggar basin. Coring of J2x, J1s, J1b formations is carried out to test the drillability, hardness and uniaxial compressive strength and the ROP of these formations is lower than 1 m/s.(Bao Heng et.al, 2021) The experimental results are shown in Table 1.

| Table 1. Indoor test data in Central China (mean value). |
|-----------------|--------|--------|--------|
| Formation       | J2x    | J1s    | J1b    |
| Drillability of cone bit | 7.10   | 6.70   | 6.07   |
| Drillability of PDC bit | 7.02   | 6.79   | 6.53   |
| Hardness(MPa)   | 1028.9 | 718.47 | 648.83 |
| Compressive strength (MPa) | 143.69 | 106.73 | 123.68 |
| Abrasiveness    | 6.35   | 5.17   | 6.08   |
It can be seen from the table that the hardness of Jurassic formation is high and the drillability grade value is relatively high. The differences of drillability grade, hardness and compressive strength of each formation are small. The values of J_2x formation are significantly higher than those of other formations, which indicate that the formation is hard and difficult to improve ROP by conventional drilling technology. So new rock breaking means need to be explored. In order to solve the problem of efficient fracture of Jurassic strata in central Junggar basin, it is necessary to explore effective fracture mode and optimal evaluation method.

3. Study on Analysis and Evaluation Method of Impact Crushing Efficiency

3.1. Experimental Device

The rock burst testing system includes power system, testing system and rack. The power system includes detonation device (or high-pressure gas source), servo motor and power supply; the test system includes laser source, strain test module, computer, etc.; the rack includes launch tube, hammer, input rod, output rod, etc. (Huang Zhiqiang, 2009; Guo Lianjun, 2013).

The study of dynamic mechanical properties of materials under high strain rate, the strain rate effect must be considered as well as the one-dimensional stress wave assumption. Because these two kinds of effects with each other, the theoretical analysis is very difficult. Therefore, decoupling these two kinds of effects is a key to obtain the dynamic mechanical properties of materials under high strain rate. Based on the above understanding, the Hopkinson pressure bar technology successfully developed to the separated Hopkinson pressure bar device. Its simplified structure is shown in Figure 1

![Figure 1. Schematic diagram of split Hopkinson pressure bar device.](image)

The incident pulse strain \( \varepsilon_i(X_1,t) \), the reflected pulse strain \( \varepsilon_r(X_2,t) \) and the transmitted pulse strain \( \varepsilon_t(X_2,t) \) at the \( X_j \) interface are obtained by means of the strain gauges pasted on the input rod \( X_1 \) and the output rod \( X_2 \). The dynamic stress \( \sigma(t) \) and strain of the specimen \( \varepsilon_S(t) \) can be obtained:

\[
\begin{align*}
\sigma_S(t) &= \frac{EA}{A_S} \left[ \varepsilon_i(X_1,t) + \varepsilon_r(X_1,t) \right] \\
\varepsilon_S(t) &= \frac{2C_0}{l_S} \int_0^t \left[ \varepsilon_i(X_1,t) - \varepsilon_r(X_1,t) \right] dt
\end{align*}
\]

\( A \) — Cross sectional area of strut, \( m^2 \); \( A_S \) — Cross sectional area of rock sample, \( m^2 \); \( \sigma_i(t) \) — Pulse load at \( X_1 \), MPa; \( \sigma_r(t) \) — Pulse load at \( X_2 \), MPa; \( \nu_i(t) \) — Pulse velocity at \( X_1 \), m/s; \( \nu_r(t) \) — Pulse velocity at \( X_2 \), m/s; \( E \) — Elastic modulus of compression bar, MPa; \( C_0 \) — Longitudinal wave velocity of compression bar, m/s; \( \varepsilon_i(X_1,t) \) — Incident pulse strain at \( X_1 \); \( \varepsilon_r(X_1,t) \) — Reflected pulse strain at \( X_1 \); \( \varepsilon_r(X_2,t) \) — Transmission pulse strain at \( X_2 \).

The one-dimensional stress wave assumption and the stress uniformity assumption should both be satisfied. Because the incident wave and the transmitted wave propagate in the specimen. Therefore, as long as the specimen is short enough, the stress/strain distribution along the length direction of the
specimen will be uniform immediately, which can meet the stress uniformity assumption. So the "three wave method" based on the theory of elastic stress wave propagation in slender rod is used in SHPB(split Hopkinson pressure bar) experimental data processing. Compared with other methods, the "three wave method" has higher accuracy.

\[
\begin{align*}
\sigma_s &= \frac{E A [\varepsilon_i + \varepsilon_r + \varepsilon_s]}{2 A_s} \\
\dot{\varepsilon}_s &= \frac{(\varepsilon_i - \varepsilon_r - \varepsilon_s) C_0}{l_s} \\
\varepsilon_s(t) &= \int_0^t \dot{\varepsilon}_s \, dt
\end{align*}
\]  

(2)

\(\sigma_s\) —Dynamic stress of rock sample, MPa; \(\dot{\varepsilon}_s\) —Dynamic strain rate of rock sample, s\(^{-1}\); \(\varepsilon_s(t)\) —Dynamic strain of rock sample; \(l_s\) —Initial thickness of rock specimen, m; \(\varepsilon_i\) —Incident pulse strain signal; \(\varepsilon_r\) —Reflected pulse strain signal; \(\varepsilon_t\) —Transmission pulse strain signal.

3.2. Impact Test Scheme

The rock samples of J2x, J1s and J1b are mainly used in the experiment. Because the impact power (velocity) is the main factor which affecting the impact effect, the average method is used to study the effect of impact velocity on the crushing of different rock samples, and each velocity is repeated three times under each confining pressure condition. The experimental scheme is shown in Table 2.

| Formation | Impact velocity | Confining pressure |
|-----------|----------------|--------------------|
| J2x       | 4              | 3                  |
| J1s       | 4              | 3                  |
| J1b       | 4              | 3                  |
| Total     | 12             | 3                  |

4. Experimental Result

4.1. Analysis of Crushing Form in Impact Test

The crushing test of rock samples in J1s was done, the failure forms showed in Fig. 2. It shows that with the increase of impact rate, the damage degree of rock is more serious, and the diameter of fragments is smaller. When the impact rate is small, the rock sample will be broken after one impact, which indicates that the rock is brittle, and the application of small load can exceed the failure threshold of the rock, causing brittle failure of the rock; with the increase of impact speed, the damage of shock wave inside the rock is intensified, and the crack propagation direction is not only along the direction of minimum stress, so the fragmentation degree is intensified, and the block size particles are more uniform and fine.
According to the measurement of mass and frequency relationship, the distribution equation of rock fragmentation can be obtained as follows:

\[ Y = \frac{M(x)}{M_T} = \left( \frac{x}{x_m} \right)^{3-D_b} \]  

(3)

\( x \) —— the particle size, m; \( x_m \) —— the maximum size of broken rock, m; \( D_b \) —— the fractal dimension of fragmentation distribution; \( M(x) \) —— the cumulative mass of fragments with size less than \( x \), g; \( M_T \) —— the total mass of fragments, g.

Taking logarithms on both sides of the above formula, we can get:

\[ \log Y = \log \left[ \frac{M(x)}{M_T} \right] = (3-D_b) \log \left( \frac{x}{x_m} \right) \]

(4)

According to the formula (4), the slope of fitting line in \( \log [M(x)/M_T] - \log x \) coordinate is \( (3-D_b) \). It shows good self-similarity of the broken rock. Under the impact load, the fractal dimension of rock fragments is mainly between 0.9 and 2.9.

According to \( D_b = 3-K \), the fractal dimension of each impact velocity is calculated as the fractal dimension of rock fragments, and the curve of fractal dimension changing with loading rate is obtained as shown in Figure 3.
From the relationship between fractal dimension and impact rate, it can be seen that the fractal dimension of C2b rocks increases with the increase of loading rate, which is approximately linear. With the impact rate no less than 12 m/s, the fractal dimension increases obviously, which indicates that the diameter of rock fragments in C2b decreases greatly, the degree of fragmentation intensifies, and the fragmentation is more uniform after the impact rate is greater than 12 m/s. It is speculated that the optimal impact rate for C2b rocks is close to 12 m/s.

4.2. Impact Test Results

The impact fracture experiments were carried out on three strata samples of J2x, J1s and J1b, and the results are shown in Fig.4.

According to the experimental results of J1b, the rock type is mainly tight sandstone with high hardness, and the deformation is mainly elastic or elastic-plastic under impact load, so when the impact velocity is 4 m/s, the rock does not break with one impact, and the rock is broken after 10 consecutive impacts. Therefore, increasing the impact frequency is helpful to improve the efficiency of rock breaking for J1b rocks. With the increase of impact rate, the proportion of large-size fragments decreases. When the impact rate increases to 12 m/s, the proportion of particle size distribution is basically the same as that of 8 m/s. The rock is also broken under 30 MPa confining pressure. When the impact rate increases to 16 m/s, the proportion of large-size fragments decreases rapidly, and the proportion of small-size fragments increases rapidly. The proportion of fragments less than 20 mm accounts for about 60%. It can be seen that the J1b rocks have the best impact rate; the impact speed is not less than 12 m/s.

According to the experimental results of J2x, with the increase of loading rate, the degree of fragmentation is more serious, and the grain size is finer. It shows that when the load exceeds the failure threshold of rock, the rock sample is subjected to the action of shock wave, the degree of crack propagation is intensified, and the rock broke with brittle fracture. When the impact rate is 12 m/s, the fragmentation less than 20 mm accounts for about 45 %, and the rock is also broken under 30 MPa confining pressure. Increasing the impact rate to 16 m/s, the fragmentation of rock is all less than 20 mm, which is consistent with that of 12 m/s. Therefore, according to the fragmentation analysis of
impact fragments, the optimal impact rate of J2x tight sandstone is 12 ~ 16 m/s. From the experimental results of J1s, with the increase of loading rate, the grain size becomes finer; when the impact load exceeds the failure threshold of rock, brittle failure occurs, the impact rate continues to increase, the failure stress is greater than the maximum principal stress of rock, and the rock sample is completely broken. When the impact rate is less than 8 m/s, the proportion of fragments less than 20 mm is less than 10 %, and when the impact speed increases to m/s. When the impact velocity is increased to 16 m/s, the specific gravity increases to about 90 %. It shows that the impact velocity of J1s should be increased to more than 12 m/s in order to achieve better rock breaking effect. According to the above test results, with the increase of impact rate, the diameter of fragments becomes smaller, and the impact strength of J1s rock is larger, and the optimal impact rate is more than 12 m/s. The rock of J2x has high impact strength, and the best impact rate is 12 ~ 16 m/s. The rock of J1b has low impact strength, and the best impact rate is 8 m/s. For the Jurassic formation, the impact rate should be bigger than 12 m/s, so this result must be referred to the next tool design and adjust the impact speed of the impact tool to increase the impact speed.

5. Conclusions and Suggestions
The main rock types of Jurassic J2x, J1s and J1b formations are tight sandstone with high hardness. Increasing the impact frequency is helpful to improve the efficiency of rock breaking. The best impact rate of rock is not less than 12 m/s. It is recommended that the combination of percussion tool and PDC bit can effectively improve ROP. It is suggested that a suitable anti percussion PDC bit should be selected or developed to cooperate with it. It is also suggested that the technology should be applied to deep and difficult formations.

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