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Lab investigations of percussion drilling: from single impact to full scale fluid hammer

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ABSTRACT: Lack of fundamental understandings of the physical mechanisms involved in percussion drilling limits hammer development and performance control. In this study, a series of lab investigations have been designed and executed. The tests are divided into two categories: single impact tests with an indentor and full scale fluid hammer tests under field conditions. Both Berea sandstone and Mancos shale samples are used. For each impact test, three impacts are sequentially loaded at the same location to investigate rock response to repetitive loadings. After each impact, crater depth and width are measured. Various pressure differences across the rock-indentor interface are used to investigate the pressure effect on rock penetration. For hammer drilling tests, an industrial fluid hammer is used to drill Berea sandstone and Mancos shale under both underbalanced and overbalanced conditions. Cuttings are collected and analyzed after the tests. The data and findings from the tests advance the understandings of the rock physics involved in percussive drilling. They also serve to calibrate a dynamic numerical model developed for percussion drilling.

1. INTRODUCTION

Percussion drilling has long been considered an effective approach to breaking rock in the civil and mining industries. It did not, however, gain much acceptance in oil and gas industries until the 1980's when a large number of air hammers were introduced in the field [1-3]. Publications on fluid hammers, to meet the challenges associated with drilling deep and hard rocks, were first presented in 1990s [4]. Since then the industry has consistently pursued improvements in hammer design, performance, and reliability [4-6].

Despite these efforts, fundamental understandings of the physical mechanisms involved in percussion drilling remain as a significant challenge. This has limited hammer development and performance control. For example, lab tests have shown that crater volume remains constant [7] or increases little [8] if only the horizontal stress parallel to the bottom surface is increased while the difference between bottom hole pressure (BHP) and pore pressure (PP) is held constant. Increase of the absolute value of either BHP or pore pressure changes rate of penetration (ROP) little too [9]. It is the difference between BHP and PP that affects ROP a great deal [9-11]. There are several speculations on the mechanisms for ROP reduction with BHP in traditional rotary drilling, such as effective loading stress decreases as a result of increase of BHP, or higher confining stress around the rock results in higher rock compressive strength. However the reason why such penetration reduction in percussion drilling remains unclear. There are also confusions about the field observations that hammer drilling in shale usually poses much greater challenges than other types of rock.

The lack of fundamental understandings of rock mechanics involved in percussion drilling is partially due to the limited availability of rock dynamics data during bit-rock impact, especially close to the impact location. The authors have to trace back to 1960s [12] to find rock displacement record during one indentation test. Recently there have been efforts made to improve the understandings of rock physics in percussion drilling and thereby facilitate more efficient and lower cost drilling and exploration of hard-rock reservoirs in percussion drilling tests [13-15]. In this study, a series of lab investigations have been designed and executed. Particular interests are paid to the effect of rock type, as well as pressure difference between BHP and rock pore pressure, on hammer penetration. The data from the tests is also used to calibrate a 3D drilling simulator developed for percussion drilling (see details of the simulator in reference [15]).

2. OUTLINE OF TESTS

The tests can be divided into two categories: impact tests with single indentor and full-scale fluid hammer tests under field conditions. Both Berea sandstone and Mancos shale are used as samples. Their mechanical properties, including moduli, Poisson's ratio, cohesive strength, friction angle, tensile strength, etc., are first determined from confined triaxial tests and Brazilian tests.

For each impact test, three impacts are sequentially loaded at the same rock location to investigate rock response to repetitive loadings. After each impact, crater depth and width are measured and rock debris is washed out to leave a clean rock surface for the next impact. Meanwhile both the displacement and force in the rod and the force in the rock are recorded at high frequency level of about 100KHz. Various pressure differences across the rock-indentor interface (i.e. bore pressure minus pore pressure) are implemented to investigate the pressure effect on rock penetration.

For hammer drilling tests, an industrial fluid hammer is used to drill both Berea sandstone and Mancos shale under both underbalanced and overbalanced conditions. The bottom hole pressure varies from 3.4MPa to 20.7MPa while pore pressure is controlled separately, varying from 0psi to 24.2MPa. Water-based mud weighting 1.2g/cm^3 circulates fast enough to clear failed rocks at the hole bottom. During the tests, ROP is recorded continuously from one pressure condition to another. Cuttings are collected and analyzed after the tests.

3. SINGLE IMPACT TEST

In the single indentation tests, a conical cutter impacts Berea sandstone and Mancos shale rock samples measuring 0.1334m (5.25 inches) in diameter by 0.0921m (3.625 inches) in height. Besides the crater size, three other measurements are taken, including dynamic force in the rock and dynamic displacement and force in the steel rod. There are two objectives of the tests. First is to investigate the effect of sequential impacts on rock dynamic behaviors and failure; second to study rock breakage under different BHP and pore pressure combinations.

3.1. Testing Matrix

The matrix of the impact tests are listed in Table 1. Total twelve impact tests were conducted. For each rock type, two different BHP and PP combinations were implemented. For each test, three impacts were sequentially loaded at the same location. For Mancos shale, because of its low permeability, the pore pressure was not changed during the tests.

Sample	BHP(psi)	PP (psi)	DP (psi)	# of Impacts
Mancos Shale	0	0	0	3
Mancos Shale	2000	0	2000	3
Berea Sand	0	0	0	3
Berea Sand	3000	2500	500	3

Table 1. Testing matrix for single impact tests

3.2. Equipment and Procedures

Indentation tests were performed on a Single Insert Impact Tester [13]. As indicated in Fig. 1, the rock sample was loaded inside the pressure vessel, and exposed to drilling mud (for high pressure tests). The single insert was located tightly against the rock at a given pre-load on the rock. A steel anvil with a single insert attached at the bottom extends out of the pressure vessel and upward through a hollow piston. A gas driven piston was used to strike a shoulder on the anvil, at about the mid length of the anvil. This impact sent a compressive stress wave down the anvil, through the insert, and into the rock. The magnitude of the stress wave is determined by the velocity of the gas driven piston at the time it strikes the anvil shoulder. Both piston velocity and the time duration of the impact can be controlled by the travel of the gas driven piston before it "bottoms out" against the piston cylinder end plate.

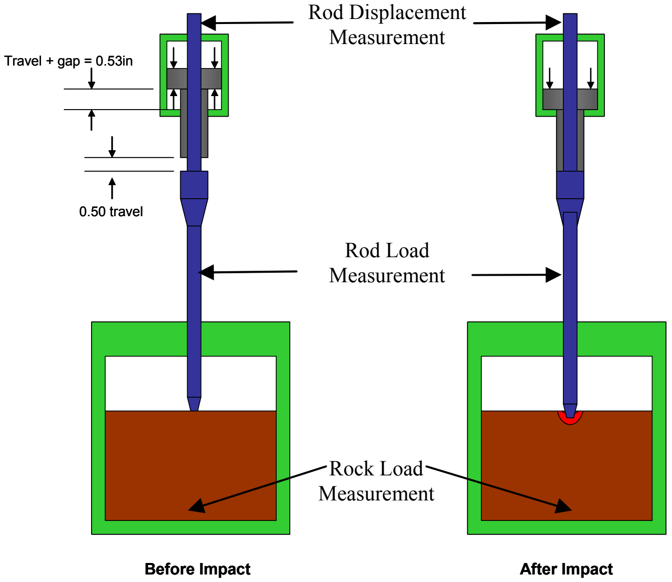

Fig. 1. Schematic representation of test setup for single impact tests.

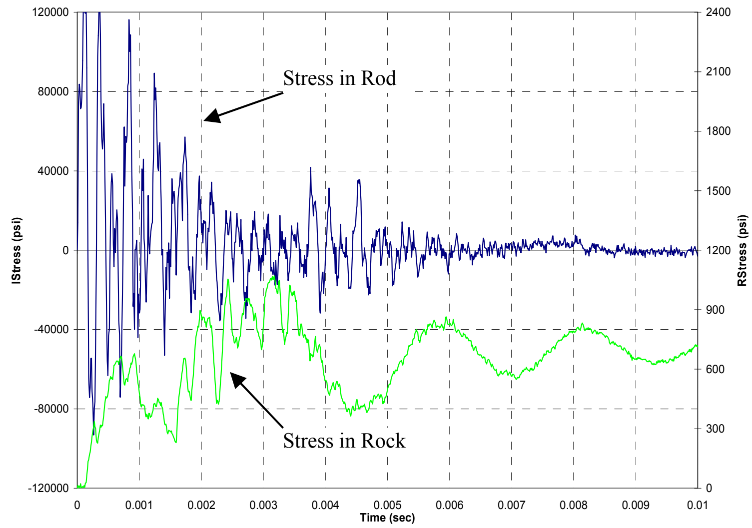

Fig. 2. Compressive stresses recorded in the rod and the rock in a single impact test with 0psi confining stress and 0psi PP

During the test, the load in the steel rod (ILoad) was measured by a load cell located outside the pressure vessel, the displacement of the rod (IDispl) was recorded by a high frequency-high resolution laser measuring device on the upper end of the anvil, and the load at the rock bottom was assessed by a rock load cell (RLoad) pre-loaded against the bottom of the rock directly in line with the insert impact (see Fig. 1). Data was recorded at 91 KHz for about one second. The crater depth and diameter were measured after the test was completed; then the rock debris was washed out to leave a clean rock surface for the next impact test.

3.3. Observations and Findings

In a test with Berea sandstone at 0psi confining stress and 0psi pore pressure, the impact stress in the steel rod, calculated from ILoad, and the dynamic compressive stress in the rock, calculated from RLoad, are plotted and Fig. 2. The magnitude of stress wave generated by the piston can reach as high as 120kpsi (827.4MPa) in the steel rod, and oscillate at a frequency of 3kHz or so. After passing from the rod to the rock, the stress wave will gradually lose its energy due to rock damping effect [15]. When the wave reaches the bottom of the rock where the load is cell located (approximately 0.12 millisecond), less than 1100psi remains. Even though the loading stress in the rod diminishes after 0.01sec, the rock stress oscillates around 700psi because of the remaining gas pressure in the vessel. Fig.3 describes the first wave in the rod.

Besides the stresses, the displacement in the rod is also monitored during the impact. Fig. 3 describes the rod displacement in the first cycle of the impact. Rod deformation increases first, levels off after the stress in the rod (calculated from ILoad) becomes tensional and keeps increasing when next cycle of compressive waves arrive.

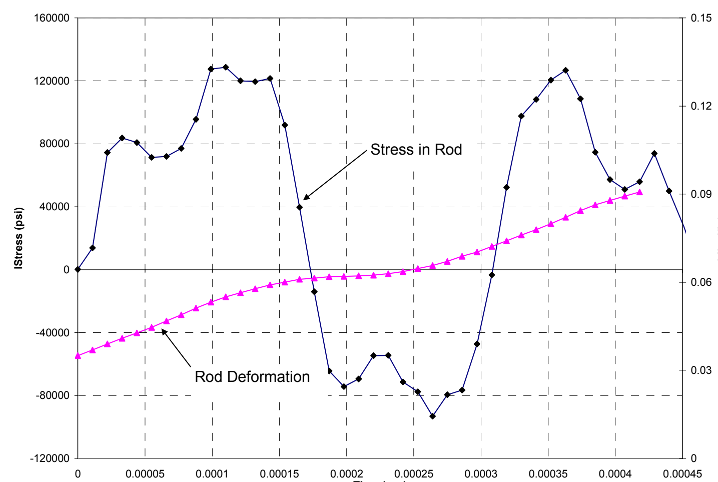

Fig. 3. Compressive stress and displacement of the rod.

After each impact the pressure is released and crater depth and radius are measured. Debris are washed out so that a fresh rock surface can be exposed for the next impact. As an illustration, Fig. 4 compares the craters in Mancos shale (left) and Berea sandstone (right) with 0psi confining and pore pressure. The numbers in each picture indicate the sequence of the impacts.

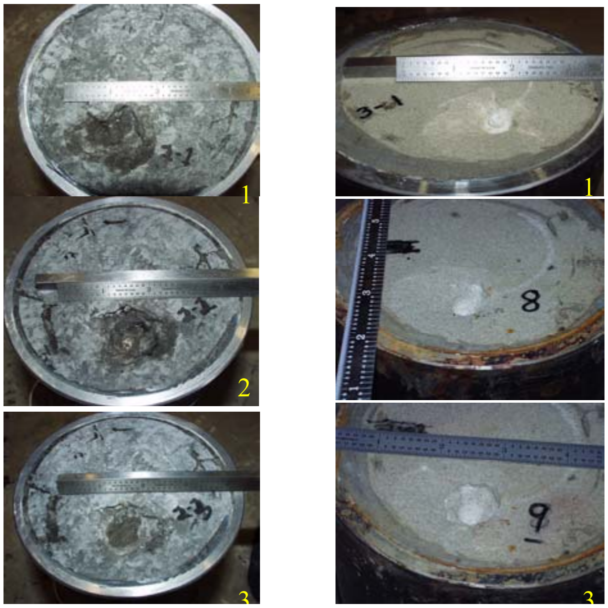

Fig. 4. Rock damage after three impacts on the same rock location (left: Mancos shale; right: Berea sandstone).

Sample #1: Berea Sandstone					Sample #2: Berea Sandstone				
Test #	BHP	PP	DP	Inches	Hammer ΔP	BHP	PP	DP	Inches
1.1	2000	0	2000	2	2.1	3000	2000	1000	2
1.2	2000	500	1500	5	2.2	3000	2500	500	5
1.3	2000	1000	1000	8	2.3	3000	3000	0	8
1.4	2000	1500	500	11	2.4	1000	0	1000	11
1.5	2000	2000	0	14	2.5	1000	500	500	14
1.6	2000	2500	-500	17	2.6	1000	1000	0	17
1.7	2000	3000	-1000	20	2.7	1000	1500	-500	20
1.8	2000	1000	1000	23	2.8	1000	2000	-1000	23
1.9	2000	2000	0	26	2.9	3000	3000	0	26
1.10	2000	3000	-1000	29	2.10	3000	2000	1000	29
				32					32
Sample #3: Berea Sandstone					**Sample #4: Mancos Shale**				
Hammer ΔP	BHP	PP	DP	Inches	Hammer ΔP	BHP	PP	DP	Inches
3.1	0	1000	-1000	2	4.1	200	0	200	2
3.2	500	1500	-1000	5	4.2	500	0	500	5
3.3	1000	2000	-1000	8	4.3	1000	0	1000	8
3.4	1500	2500	-1000	11	4.4	1500	0	1500	11
3.5	2000	3000	-1000	14	4.5	2000	0	2000	14
					4.6	200	0	200	17
					4.7	500	0	500	20
					4.8	1000	0	1000	23
					4.9	1500	0	1500	26
					4.10	2000	0	2000	29
									32

Table 2. Testing matrix for full-scale mud hammer drilling.

4. FULL SCALE HAMMER DRILLING TESTS

4.1. Testing Matrix

Four rock samples including three Berea sandstones and one Mancos shale measuring 15 inches (39.4cm) in diameter and 36 inches (91.4cm) in length, were used in full-scale drilling tests. Four sets of drilling tests were conducted with an industry mud hammer bit at both overbalanced and underbalanced conditions. The BHP changed from 0psi to 3000psi (20.7MPa) while the pressure difference across rock surface varied from -1000psi (-6.9MPa) to 2000psi (13.8MPa). The hammer bit drilled 3 inch rock sample under each pressure condition.

4.2. Equipment and Procedures

The drilling tests were conducted in a wellbore simulator [13] under field downhole conditions. After being placed on a steel endcap and enclosed inside a urethane jacket, the jacketed rock sample was then pressurized with confining fluid to simulate the horizontal earth stresses, and an independent piston applied an axial thrust to the sample to simulate the overburden stress. For the Berea sandstone samples, they were saturated prior to the tests and back pressure at the bottom end cap was controlled during the tests to create either an overbalanced or underbalanced drilling condition with pore pressure inside the rock. The servo-controlled drill rig allowed control of constant torque for the mud hammer tests.

A 74.9lb/ft^3 (1.2g/cm^3) water-based drilling fluid was circulated through the mud hammer, up the drilled annulus, and through a cuttings-removal screen. An adjustable choke was used on the drilling fluid return line to control borehole pressure. The drilling fluid temperature was maintained constant by passing it through a heat exchanger.

Data were recorded at a frequency of 1 Hz during the test. In addition to that, bursts of high rate data were recorded at 2000 Hz for 2 seconds. Data contains distance drilled, penetration rate, penetration per revolution, torque, weight on bit, rotary speed, borehole pressure, swivel pressure, back pressure, flow rate, drilling fluid temperature, overburden stress, confining pressure, mechanical horsepower, bit pressure drop, and summaries of drilling fluid properties. The mechanical and hydraulic parameters are arithmetic averages over the interval.

After removing the mud hammer from the vessel, the samples top end cap was unbolted and the top vessel plug/bit assembly was raised up to expose the bit. The cuttings collected in the collection screen were then examined, photographed, and the volume of cuttings measured.

4.3. Observations and Findings

The data for rate of penetration vs. pressure difference (ΔP) across rock drilling surface is summarized in Fig. 5. While in Berea sandstone, ΔP refers to the pressure drawdown across the filter cake on the hole bottom, it is equal to BHP in Mancos shale since the pore pressure was not changed. Drillings in both Berea sandstone and Mancos shale are plotted for comparison. Generally, ROP in both rocks drop quickly with increasing difference in pressure. For example, ROP decreases from 70 ft/hr to 7ft/hr after the BHP climbs from 500psi to 2000psi. As expected, the mud hammer has performed very well in underbalanced drilling conditions, ROP can reach 75 ft/hr when the ΔP is -500psi. On the other hand, under the same pressure condition, the mud hammer performed better in Mancos shale. The ROP can reach as high as 70 ft/hr when the pressure difference is 500psi (3.45 MPa), compared to 23 ft/hr in Berea sandstone. This ROP difference, however, should not lead one to believe that the mud hammer is preferred in shale. One reason is that the shale samples in these tests are not saturated. More important, each ΔP value in the plot corresponds to different formation depths depending on whether or not the rock is permeable. In fact, field evidence has suggested that shale formation usually poses more challenges for hammer drilling than sandstone.

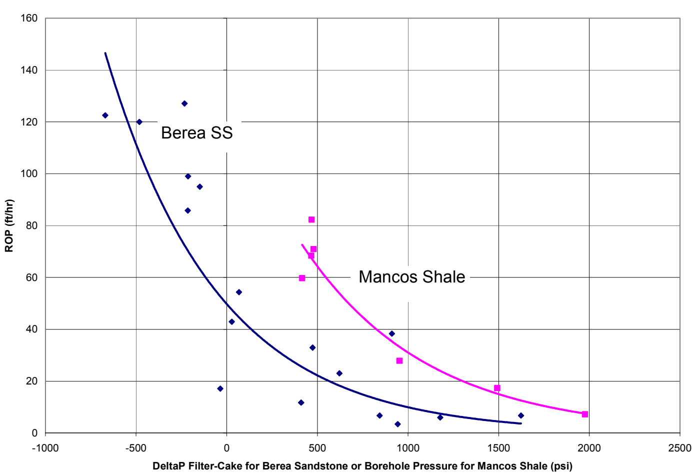

Fig. 5. Recorded drilling progress in hammer tests with various ΔP.

A drilled rock sample is photographed in Fig. 6, which also includes the cuttings collected from a roller-cone drilling, an underbalanced hammer drilling, and a penny coin for comparison. Even though the size of the cutting from the hammer bit is not as big as that from the roller-cone bit, it is as thin as a penny coin (i.e. disk shape) while the cuttings from the roller-cone bit is a chunk. This may indicate different failure mechanisms involved in each of the two drilling methods, as discussed in the next section.

Fig. 6. One drilled rock sample and collected cuttings from a roller cone drilling test and a hammer drilling test.

5. RESULTS AND DISCUSSIONS

After collecting and analyzing the test data, some interesting findings regarding the effect of repetitive impacts, rock type, and pressure difference on rock drillability are discussed as follows.

5.1. *Effect of Repetitive Impacts on Drilling Depth*

Three impacts were loaded on the same location on the top of the rock surface. After each impact, the depth and width of craters were measured. Plotting the penetration depth against the number of loadings in Fig. 7, we can clearly see a different trend of penetration performance between Mancos shale and Berea sandstone. For Berea sandstone, the crater depth after each impact increases with number of impacts (except the third one at 0 psi fluid pressure, which may be an abnormal test point). This agrees with the proposed concept that rock becomes weaker (fatigue) due to cyclic loading [15]. However, for Mancos shale (dash lines in Fig. 7), the crater depth decreases with number of impacts. Since the energy level of each impact is constant, this indicates the rock, instead of being weakened by repetitive loadings, is actually stronger than the original. We believe the discrepancy results from the difference of the rock structures. Berea sandstone is a porous (porosity is 20.5 percent) and medium strength rock (UCS is 45.9MPa), whose particles more easily shift and rearrange to accommodate the loading stress. Micro-fissures are easily introduced while particles shift and loading force increases. Mancos shale is a more compact (porosity is only 7.9 percent) and highly layered rock with higher strength (UCS is 55.7MPa). When hammer impacts the shale, the shale particles are more likely crushed into smaller powders instead of moving to a porous space. Crushed particles, as a new material, have more strength and higher density than the original rock, which explains why Mancos shale becomes stronger after each loading.

the mud hammer is fast enough to maximize hammer efficiency.

These findings are one example that demonstrates the complexity of percussion drilling. Hammer performance is not only related to the cutter and bit design and the percussive energy level that a hammer can create, but also to the rock mechanical properties, flow properties, and structure. Different types of rocks may have the same strength, but a hammer may perform quite differently because of the difference in rock structures. In our case, even though Mancos shale is more competent and stronger than Berea sandstone, the hammer performed better in the drilling simulator.

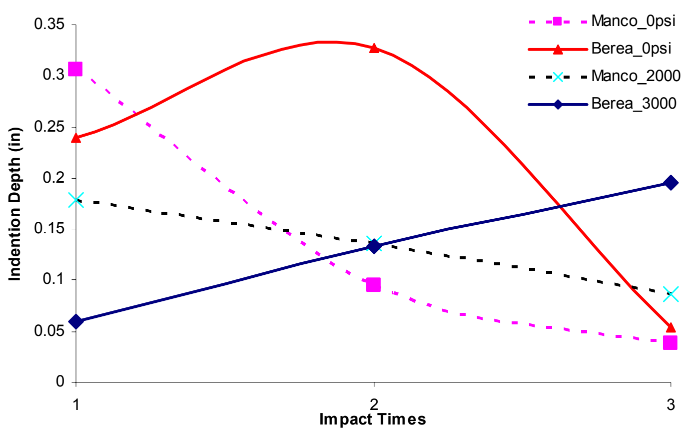

Fig. 7. Indentation depths with number of impacts in single impact tests

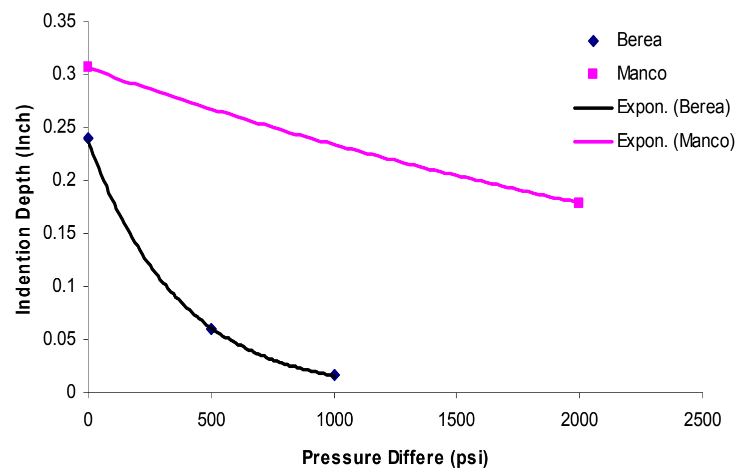

Fig. 8. Indentation depth vs. pressure difference in single impact tests

5.2. Effect of Rock Type

Also it should be noted that in Fig. 7 the indentation depth after the first impact in Mancos shale (0.31 in) are higher than those in Berea sandstone (0.24 in). This is mainly due to the layered structure of the shale which facilitates rock tensile failure even though it is stronger than Berea sandstone in compression. The chips can more easily detach from the rock matrix due to the low cohesion between layers. To avoid crushing particles and encourage rock tensile failure, the bit needs to rotate to help cutters find next fresh rock surface. Too slow or too fast rotation may limit hammer performance in the shale because of the compacting effect discussed above. This finding is confirmed by the results from full-scale hammer tests (Fig. 5), which shows that the hammer has performed better in Mancos shale than in Berea sandstone. In the drilling tests, this also indicates that the rotation of

5.3. Effect of Pore Pressure and BHP

The effect of pressure difference across rock drilling surface on drilling performance has been given much attention for a long time [7-11, 16]. Considerably fewer publications document similar pressure effects in percussion drilling [13]. There is a lot of speculation on the mechanisms, such as a decrease in effective loading stress with increase of BHP, or that higher confining stress around the rock results in higher rock compressive strength. Based on the cuttings collected in full-scale hammer drilling, and integrated theoretical modeling efforts [15], we believe because there is no compressive stress on the rock surface and rock tensile strength is much less than its compressive strength, the rock may more easily break in tension when the bit retreats in hammer drilling. In Fig. 6, the chip-shaped cutting indicates a tensile nature in rock breakage when the hammer drilled under an underbalanced condition. Because of the encouraging hammer performance in such condition, any design or operation that encourages such failure mechanism may significantly improve mud hammer performance.

6. SUMMARIES

Percussion drilling has long been considered an effective approach to break rock in civil and mining industries. It has not, however, gained much acceptance in oil and gas industries because of a poor understanding of rock defragmentation, risks in drilling operations, and economical uncertainties. To improve the knowledge of the physics of rock failure and facilitate theoretical modeling efforts to simulate the process of percussion drilling, a series of lab investigations have been designed and carried out.

These tests can be divided into two categories: single impact tests with single indentor and full scale fluid hammer tests under field conditions. Both Berea sandstone and Mancos shale were used as samples. While the samples in the impact tests are 5 inches (diameter) by 4 inches (depth), those in the hammer tests are 15 inches (diameter) by 36 inches (length).

- For each impact test, three impacts are sequentially loaded at the same location to investigate rock response to repetitive loadings. After each impact, crater depth and width were measured and rock debris washed out to leave a clean rock surface for the next impact test. Meanwhile both the displacement and force in the rod and the force in the rock were recorded at high frequency level of about 100K Hz. Various pressure differences across the rock-indentor interface (i.e. bore pressure minus pore pressure) were implemented to investigate the pressure effect on rock penetration.
- For hammer drilling tests, an industrial fluid hammer was used to drill both Berea sandstone and Mancos shale under both underbalanced and overbalanced conditions. The bottom hole pressure varies from 500psi to 3000psi while pore pressure is controlled separately, varying from 0psi to 3515psi. During the tests, Rate of Penetration was recorded continuously from one pressure condition to another. Cuttings were collected and analyzed after the tests.

Besides calibrating a dynamic numerical model developed for percussion drilling, the data and cuttings collected from the tests indicate several important applications. For example, different rock penetrations during single impact tests may reveal why fluid hammer behaves differently with diverse rock types and under various pressure difference at the hole bottom. On the other hand, the shape of the cuttings from fluid hammer tests, compared to those from traditional rotary drilling methods, may help to identify the dominant failure mechanism that percussion drilling relies on, and therefore improve hammer performance through encouraging such failure mechanism.

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