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Effect of Grain Size and Grain Content on the Hardness and Drillability of Rocks

(Kesan Saiz Butiran dan Kandungan Butiran terhadap Kekerasan dan Kebolehgerudian Batuan)

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ABSTRACT

It is well-known that the characteristics of hardness and drillability are influenced by microstructure of rock. In this study, rock properties were analyzed on grain size and grain content. Coarse-grain and fine-grain sandstones were tested under successive indentation condition. Eighteen groups of sandstone and shale were employed for the drillability test. Indentation tests results showed that grain size influenced the low point of residual hardness, the crushing depth and volume and grain content influenced the peak point of hardness. The drillability values of shale increased with increasing contents of clay and quartz. Meanwhile, drillability values of sandstone increased with increasing content of quartz, but decreased with increasing content of clay. Therefore, these preliminary studies show great potential applications for selecting suitable bit type and formulating drilling program as a function of rock microstructure and crushing rock method for bit in the oil drilling.

Keywords: Drillability; grain content; grain size; hardness; successive indentation

ABSTRAK

Adalah diketahui sifat kekerasan dan kebolehgerudian batuan dipengaruhi oleh mikrostruktur batuan. Dalam kajian ini, saiz butiran dan kandungan butiran beberapa batuan dianalisis. Batu pasir bersaiz butiran kasar dan halus diuji dengan keadaan pelekukan berterusan. Lapan belas kumpulan batu pasir dan syal digunakan untuk ujian kebolehgerudian. Ujian pelekukan menunjukkan saiz butiran mempengaruhi kekerasan baki titik rendah, kedalaman kehancuran dan isi padu manakala kandungan butiran mempengaruhi kekerasan titik tinggi. Nilai kebolehgerudian syal meningkat dengan peningkatan kandungan lempung dan kuartz. Untuk batu pasir, nilai kebolehgerudian meningkat dengan peningkatan kandungan kuartz, tetapi menyusut dengan peningkatan kandungan lempung. Hasil kajian awal ini menunjukkan keupayaan tinggi kaedah ini dalam pemilihan mata gerudi yang sesuai dan merancang kaedah penggerudian sebagai fungsi mikrostruktur batuan dan kaedah penghancuran batuan untuk penggerudian minyak.

Kata kunci: Kandungan butiran; kebolehgerudian; kekerasan; pelekukan berketerusan; saiz butiran

INTRODUCTION

As known to all, mechanical properties and drillability of rocks could be affected by the grain size of rocks. Mindlin (1963) reported that increasing strain gradients appeared to make some materials stronger and to a degree that depended upon the grain size. Singh (1988) presented that samples with mean grain sizes of 1.79, 1.35 and 0.93 mm showed fatigue strengths of 87.0, 88.3 and 89.1%, respectively. Moreover, they concluded that smaller grain size possessed higher value of fatigue strength. Hoseinie et al. (2009) showed that the rock grains became finer and the texture was denser, resulting in decreasing the rate of drilling and rock mass drillability.

Grain size influencing rock hardness and drillability is one of the important factors to control the growing craze of crushed rock as a result of reducing fatigue strength from the micro-analysis. Robina et al. (1996) presented that peak strength decreased with the initial crack density for fine-grain marbles, but remained relatively constant for coarse-grain marbles. Chen and Labuz (2006) and Eberhardt et al. (1999) reported that longer grain boundaries and larger intergranular cracks can make the increase of grain size that provided longer paths of weakness for growing cracks to propagate along. Koyama and Jing (2007) showed that the variance of the calculated values of mechanical properties significantly decreased as the side lengths of particle models increased using numerical procedure.

Meanwhile, grain content which also affected the wear degree of test tool was considered as a crucial factor to decide mechanical properties. Ersoy and Waller (1995) presented drilling tests using polycrystalline diamond and impregnated diamond core bits in the rock and they concluded that grain size of rock can be used as a predictive factor for assessing wear performance of rocks. Thuro (1997) put forward that drilling bit wear increased when the equivalent quartz content increased. Moreover, the equivalent quartz content built the main property for the content of wear-relevant minerals. Beste et al. (2004) also found that the wear of the tip was not only correlated to the hardness of the rocks, but also influenced by the grain size, the quartz content and isotropy.

It was clear from those previous studies that great attentions were focused on grain size and grain content which influenced the hardness and drillability. However, previous evaluation methods of the hardness were mostly obtained under single indentation process. As we know, crushing rock of bit in the down-hole was located in successive and dynamic penetration process. Moreover, the relationship between drillability and grain content can be established by some correlative theories rather than drillability tests. Therefore, in this study, as grain size and grain content influenced the hardness and drillability of rocks, successive indentations and drillability tests were subsequently conducted to comprehensively analyze grain size and grain content.

MATERIALS AND METHODS

SAMPLING

Sandstone cores were collected from 4 exploration wells with rock core of buried depth (3500-5000 m). Shale cores were obtained from natural outcrops in southwest of China for laboratory tests. Rock samples were inspected for macroscopic defects to provide test specimens free from fractures. The locations and names of rock samples were shown in Table 1.

SUCCESSIVE INDENTATION TESTS

Successive indentation tests were performed on trimmed core samples which had a diameter of 25 mm and a length-to-diameter ratio of 2. The diameter of indenter is 2.4 mm. The indentation rate was controlled at 0.01 mm/s and the test time was applied within the limits of 0.25-0.50 s (Bažant et al. 1991). When the pressure head moved 2-3 mm in the tested rock, the RTR-1000 (Rapid Triaxial Rock Test System, Geotechnical Consulting and Testing Systems, USA) was automatically shut.

DRILLABILITY TESTS

Rock drillability tests were performed on trimmed core samples which has a diameter of 40-100 mm and a length of 30-80 mm. Rollow's test conditions were shown as follows for determining drillability classification number (DCN) of different formations, the time interval was determined under the conditions of rotational speed of 55 RPM and bit weight of 890 N with 2.381 mm depth of drilling (Yin 1986). The DCN may express that 2 was the logarithm of the spending drilling time and the DCN can be classified into 10 classes which were satisfied with assessment for all kinds of rock types. The equation can be expressed as follows (Zhang et al. 2011):

$$K_d = \log_2 y \quad (1)$$

where K_d is the DCN; y is time interval of drilling with 2.381 mm depth (s).

SCANNING ELECTRONIC MICROSCOPE (SEM) TESTS

The structure and composition characterization were estimated by scanning electronic microscope (SEM) (Quanta 450, FEI, USA). All kinds of materials in high and low vacuum conditions were tested. The accelerating voltage is in the range between 200 V and 30 kV and the stable high beam currents (up to 2 μA) enable fast.

X-RAY DIFFRACTION TESTS

X-ray diffraction (XRD) test performed on X'pert MPD PRO instrument (PANalytical, Holland) was applied to evaluate the quantitative and qualitative analysis of the phase composition. The radius of angular instrument is 150 mm and the scale of measurement is in the range between -3 and 160°C. The maximum voltage and electric current of generator are 60 kV and 60 mA.

TABLE 1. Locations of tested shale and sandstone

Rock no. for sandstone	Well depth (m)	Well no. for sandstone	Rock no. for shale	Location for shale
1	4001.65-4003.36	A	10	Dayi.Chengdu, K_m: 37
2	3901.12-3915.68	A	11	Dayi.Chengdu, K_m: 42
3	3647.26-3651.88	A	12	Jiangyou.Chengdu, K_m: 315
4	3626.06-3627.93	B	13	Jiangyou.Chengdu, K_m: 322
5	3558.12-3559.79	B	14	Jiangyou.Chengdu, K_m: 345
6	3258.27-3259.35	C	15	Guangyuan.Chengdu, K_m: 460
7	3298.67-3301.73	C	16	Guangyuan.Chengdu, K_m: 465
8	3205.60-3208.36	D	17	Guangyuan.Chengdu, K_m: 530
9	3160.20-3173.42	D	18	Guangyuan.Chengdu, K_m: 579

The locations were determined as a function of geologic sedimentation order and integrality of rock specimens
K_m: kilometer

RESULTS

THE MORPHOLOGY OF ROCKS

The morphology of sandstone was measured by SEM. As shown in Figure 1, coarse-grain sandstone with the porosity of 32.3% which was larger than that of fine-grain sandstone (14.3%). Previous studies have demonstrated that uniaxial compressive strength of heterogeneous sandstones gradually decreased with the increase of porosity (Palchik 1999; Vernik et al. 1993). Meanwhile, Sulem and Cerrolaza (2002) put forward that micro-mechanisms of rock deformation process was controlled by grain rotation and grain sliding without significant grain breakage. Moreover, the deformation of coarse-grain sandstone was easier than fine-grain sandstone due to fewer cementing material inside pore volume of coarse-grain sandstone. In other word, those studies showed that the hardness of fine-grain sandstone was higher than that of coarse-grain sandstone. However, Eberhardt et al. (1999) reported that grain size has only a minor effect on the stress at which new cracks initiated by compression tests under different confining pressures. Therefore, according to above morphology of coarse-grain and fine-grain sandstones and previous research findings, it is necessary to analyze which factors influence crushed rock in successive indentation process.

COMPOSITIONS OF GRAIN CONTENT

In this study, types of mixed-layer grain and the percentage composition of grain content in the oil drilling engineering could be acquired from X-ray diffraction (XRD). The results of coarse-grain and fine-grain sandstones from XRD were presented in Table 2.

ANALYSIS OF SUCCESSIVE INDENTION TEST

In order to obtain more rock properties, indentation tests were used to characterize the mechanical behavior of rocks. The correlation between grain size and mechanical properties using indentation tests was established by some researchers. The results showed that the peak strength decreased with the increase of inverse square root of the mean grain size (Hussain et al. 2006; Szwedzicki 1998). However, these test results were based on single indentation test, which would not simulate crushing rock in the real drilling circumstance. Therefore, in this study, to comprehensively estimate the influence factor of hardness, coarse-grain and fine-grain sandstones were used to perform successive indentation tests.

As shown in Figure 2, grain size and grain content of rock affected the crushing volume and penetration depth after coarse-grain and fine-grain sandstones were successively penetrated by indenter. The penetration craters were filled with plasticine for measuring penetration volume according to the method of weigh to density. The crushing volume of coarse-grain and fine-grain sandstones were 45.7 and 38.3 mm^3, respectively and penetration depths were obtained from the axial displacement of the equipment (Figure 3).

Each key point values of hardness and displacement for coarse-grain and fine-grain sandstones (Figure 3) were listed in Table 3.

The peak point hardness values of coarse-grain sandstone were higher than that of fine-grain sandstone because quartz content of coarse-grain sandstone was higher. Thus, coarse-grain sandstone possessed better resisting penetration than fine-grain sandstone which was consisted of lower quartz content (Table 3). Therefore, it can be concluded that grain content played a more

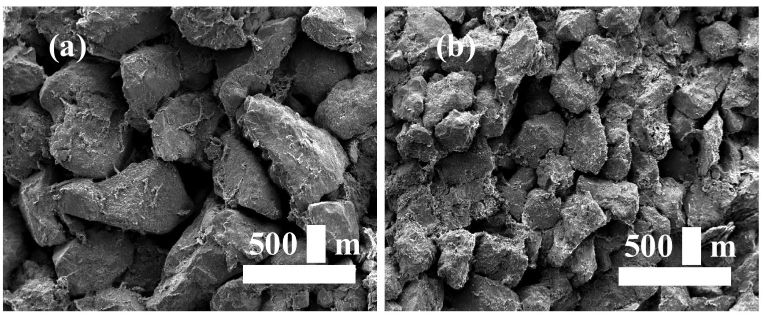
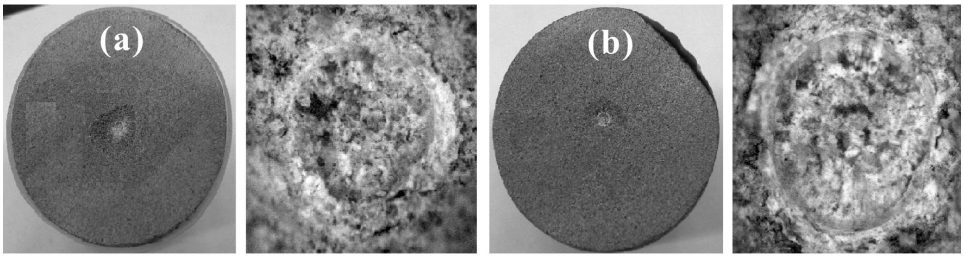


FIGURE 1. The morphology of sandstone (a) coarse-grain and (b) fine-grain

TABLE 2. The composition of grain content for coarse-grain and fine-grain sandstones

Rock type	Percentage composition of grain (× 10^{-2})						
	Quartz	Clay	Orthoclase	Plagioclase	Calcite	Dolomite	Other types
Coarse-grain	66.8	14.7	6.3	5.5	4.7	1.6	0.4
Fine-grain	52.1	33.3	6.4	3.8	2.8	1.3	0.3

The other grains included analcime and pyrite



(a) (b)

FIGURE 2. The morphology of sandstones successive indentation with a flat indenter
(a) coarse-grain sandstone and (b) fine-grain sandstone

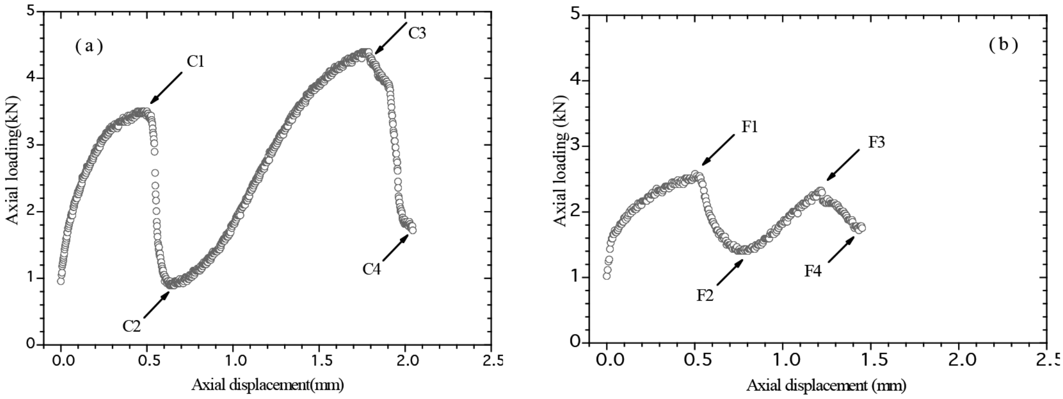


FIGURE 3. Successive indentation test for coarse-grain and fine-grain sandstones
(a) coarse-grain and (b) fine-grain sandstone

TABLE 3. The values of each key points of successive indentation test

Test values of key points	C1	F1	C2	F2	C3	F3	C4	F4
Hardness (kN)	3.47	2.55	1.06	1.44	4.36	2.20	1.82	1.88
Displacement (mm)	0.44	0.48	0.60	0.73	1.73	1.17	2.00	1.34

important role in controlling peak point hardness than that of grain size. However, the low point values of residual hardness of coarse-grain sandstone were lower than that of fine-grain sandstone. It can be attributed to the increase of displacement loading which can induce the deforming of the rock beneath the indenter in elastical cracks nuclear and the recompaction displacement was mostly decided by the rigid material of the grain size when the crushed zone was in recompacted behavior. Namely, the smaller the grain size was, the higher the low point of residual hardness. Thus, the recompaction zone of fine-grain sandstone became more densified, which can control the low point of residual hardness. This finding was in agreement with the work by Hoseinie et al. (2009), who pointed out that rock grains became finer and the hardness was higher.

The displacement of peak point hardness and low point residual hardness of coarse-grain sandstone was shorter than that of fine-grain hardness in the first indentation process, but that of displacement became longer in the second indentation progress, as shown in Table 3. One possible explanation of this phenomenon was that there were bigger grain boundaries and intergranular pores for coarse-grain sandstone than that of fine-grain sandstone, as shown in Figure 1. When the rock was pressed in the first indentation process under the low loading, the intrinsic crack length and crack initiation among the grains which had higher thresholds of crack coalescence and crack damage for the coarse-grain sandstone would not be widely propagated. When the higher loading was used in the second indentation progress, the longer grain boundaries and larger intergranular cracks provided more continuous paths of weakness for growing cracks to propagate along and promoted a more rapid degradation of material hardness once these longer cracks began to coalesce and interact due to increase grain size (Chen & Labuz 2006; Eberhardt et al. 1999). Meanwhile, the first peak point of hardness was higher than the second for fine-grain sandstone, as shown in Figure 3(b). The possible reason was that grain content and planes of weakness together restricted the grain deformation and stress distribution, leading to lower loading in the second peak point of hardness. Consequently, although the grain sizes influenced distribution of hardness, one should combine the theory with grain content and test method to make an analysis.

Results and Discussion

Rock hardness which could preliminarily predict penetrate rate and select bit type was the only static evaluation parameter. But, drillability values were obtained under certain rotation speed and drilling weigh of test condition from the Rollow's and the test process was very similar to real crushed rock circumstance in downhole (Tanaino 2008). Accordingly, the correlation of drillability and grain content was investigated in this section.

Test results of grain content

The samples of sandstone and shale were selected from Table 1 as a function of grain content of rock. The sandstone and shale were mostly consisted of clay and quart and other grain contents, as shown in Tables 4 and 5. The rock number of shale was sequenced with increasing grain content of clay, which was in the range from 39.8 to 51.7%. However, the rock number of sandstone was sorted according to decrease grain content of quartz with the range from 57.2 to 77.6%.

The results of drillablity values

The sample drillability tests of shale and sandstone were obtained as shown in Table 1. Drilling time values of microbit for shale with coefficient of variation (CoV) values were lower than 13% in the range of 14.12 to 47.18 s (Tables 6 &7) and DCN values were in the range of 3.82 to 5.36. It appeared that the value of DCN belonged to middle scale (Zhang et al. 2011). The variability of each test was within the acceptable limits for the most engineering purposes.

The drillability data of sandstone were presented in Table 7. Drilling time values were in the range of 34.06 to 99.73 s and CoV values were in the range from 5.13 to 12.13% with overall average of 8.94%. DCN values were in the range of 5.09 to 6.64.

Analysis relation of drillability and grain content

The assessment of relation between drillability and grain content were established according to experimental results of drillability and data of XRD were showed in Tables 4 to 7 and the regression results in Table 8.

The results showed a good correlation between DCN and grain content for shale and sandstone. DCN values of shale increased with increasing content of clay and quartz. Meanwhile, DCN values of sandstone increased with increasing content of quartz and DCN values of sandstone decreased with increasing content of clay. There are probably two reasons to account for the phenomenon. One was that the increase of a certain grain content of quartz was equal to increase mineral strength (Thuro 1997). The other

TABLE 4. Analytic results of grain content for shale

Rock No.	Percentage composition of grain (%)						
	Clay	Quartz	Orthoclase	Plagioclase	Calcite	Dolomite	Other types
1	39.8	27.6	10.1	14.6	5.0	2.1	0.8
2	41.1	28.3	8.4	10.3	7.8	3.7	0.4
3	42.6	29.1	8.9	11.4	6.7	1.2	0.1
4	44.1	30.2	6.6	13.6	2.1	3.0	0.4
5	45.2	32.6	9.8	8.6	1.9	0.0	1.9
6	46.7	33.4	7.4	5.1	2.8	2.4	2.2
7	47.3	34.0	10.0	5.8	0.0	2.3	0.6
9	51.7	36.1	6.1	5.7	0.0	0.3	0.1

TABLE 5. Analytic results of grain content for sandstone

Rock type	Percentage composition of grain (%)						
	Quartz	Clay	Orthoclase	Plagioclase	Calcite	Dolomite	Other types
10	77.6	18.3	2.1	0.8	0.6	0.4	0.2
11	75.1	19.8	0.6	1.2	2.3	0.9	0.1
12	73.6	22.3	0.5	2.4	6.7	1.2	0.1
13	70.2	24.1	0	3.6	0.8	1.0	0.3
14	68.4	25.6	5.2	0.3	0.2	0.1	0.2
15	66.3	27.2	0.3	0.5	4.1	0.2	0.4
16	62.1	29.4	2.6	1.0	3.3	1.2	0.3
17	60.5	30.7	0.8	2.7	4.0	0.9	0.4
18	57.2	32.4	2.7	0.6	0.4	6.2	0.6

TABLE 6. Drillability classification number of shale

Rock No.	Drilling time (s)	Standard deviation	Coefficient of variation (%)	Drillability classification number
1	14.12	1.56	11.05	3.82
2	15.56	1.92	12.34	3.96
3	18.51	1.63	8.81	4.21
4	22.01	1.69	7.68	4.46
5	24.25	2.77	11.44	4.60
6	27.67	2.13	7.70	4.79
7	32.90	2.81	8.54	5.04
8	40.51	3.41	8.42	5.34
9	47.18	3.26	6.91	5.56
Overall average			9.21	

TABLE 7. Drillability classification numbers of sandstone

Rock No.	Drilling time (s)	Standard deviation	Coefficient of variation (%)	Drillability classification number
10	99.73	5.12	5.13	6.64
11	79.34	6.46	8.14	6.31
12	69.07	4.51	6.53	6.11
13	57.28	4.76	8.31	5.84
14	52.71	5.37	10.19	5.72
15	45.57	3.25	7.13	5.51
16	41.07	4.98	12.13	5.36
17	38.59	4.27	11.07	5.27
18	34.06	4.03	11.83	5.09
Overall average			8.94	

TABLE 8. The regression results of DCN for grain content of shale and sandstone

Lithology	Grain content	Regression equation	Correlation coefficient
Shale	Clay	$K_d = 0.1588x-2.411$	0.994
	Quartz	$K_d = 0.1891x-1.3765$	0.983
Sandstone	Clay	$K_d = -0.1053x+8.4498$	0.992
	Quartz	$K_d = 0.0732x+0.7862$	0.982

was that the intergranular pores among the grains were adequately filled with enough clay, resulting in increasing clay content as same as rising crack damage thresholds for shale with constant of quartz content. Moreover, Wichtmann and Triantafyllidis (2010) also reported that sandstones with higher quartz contents reflected higher strength properties than those with lower quartz contents. In short, DCN values of sandstone and shale were mostly affected by the content of clay and quartz. Obviously, there were correlation between compressive strength and drillability as a function of quartz content.

CONCLUSION

In this study, microscopic influencing factors of mechanical properties and drillability were systematically investigated. The crushing mechanisms in the penetration process of coarse-grain and fine-grain sandstone during successive indentations were analyzed. The relation between drillability and grain content was investigated through different grain contents of sandstone and shale. The results can be summarized as follows: The peak points of hardness for coarse-grain sandstone were higher than that of fine-grain sandstone. The possible reason was that the hardness of coarse-grain sandstone increased with the increase of content of quartz; The low points of residual hardness for coarse-grain sandstone were lower than that of fine-grain sandstone. This was caused by the densification of recompaction of crushed zone which was mainly decided by grain size under the indentation. Meanwhile, the displacement of peak point hardness and low point residual hardness for coarse-grain sandstone was shorter than that of fine-grain hardness in the first indentation process, but that of displacement became longer in the second indentation progress, which were caused by grain boundaries and intergranular pores under different loading conditions; and a good relation of DCN value and grain content was obtained. Drillability values increased with increasing content of clay and quartz for shale, and drillability increased with increasing content of quartz and decreased with increasing content of clay for sandstone. Meanwhile, the correlation between drillability and compressive strength was proved by drillability test. In conclusion, we found that both of grain size and grain content had an effect on the rock properties. Moreover, the results can help in analyzing the effect of crushing rock for bit. In our further research, more and more attention would be focused on indentation and drillability tests under different confining pressures.

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