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EFFECT OF OPERATING PARAMETERS AND FORMATION PROPERTIES ON PENETRATION RATE IN SOME SANDSTONE ROCKS USING DIAMOND CORE BIT

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In this study four sandstone rocks were drilled by diamond core bit using a fixed laboratory-drilling machine at 400 and 1200 rpm, rotary speed, over a range of weights on bit (WOB) 12,18,24,30,…….,150 kg. Operating parameters of the drill bit such as WOB, penetration rates (PR), torque (T) and specific energy (SE) were continuously monitored during the drilling trials. Besides the effects of formation properties on the penetration rate were monitored. Relationships between WOB and both PR, torque T and SE were determined and the relationship between PR and SE was given. Graphs are presented and can be used to predict diamond-drilling performance easy and fast.

***KEYWORDS**: Penetration rate, rotary speed, Weight on bit, Specific energy,*

INTRODUCTION

In the rotary drilling method, the hole is drilled by a rotating bit to which a downward force is applied. Rotary drilling drills have been extensively used in many applications in our live such as water, oil, and gas well drilling and were also used in open pit mines for overburden removal. [1]

In the rotary drilling penetration rate (PR) is a very important variable due to its effects on the time and cost.

The penetration rate is very necessary for cost estimation and planning of the drilling project. Drillability and penetration rate can be defined as similar terms. Drillability indicates whether penetration is easy or difficult, while penetration rate indicates whether it is fast or slow [2, 3].

Penetration rate value is controlled by two main factors namely operating parameter and formation properties. Operational variables (operating parameters) are known as controllable parameters. Rock properties and geological conditions are uncontrollable parameters [3, 4].

The main operating parameters such as rotational speed, thrust, and flushing are the three main elements on which the driller can intervene within the limits of possibilities of the equipment. Formation properties are characteristics that effect drilling performance and are the unalterable factors [5, 6].

Drilling velocity is dependent on a lot of geological parameters: Those principal parameters include jointing of rock mass, orientation of schistosity (rock anisotropy) degree of interlocking of microstructures, porosity and quality of cementation in clastic rock, degree of hydrothermal decomposition and weathering of a rock mass. [7, 8]

The specific energy (SE) is the main index related with all drilling parameters, and can be defined as the energy necessary to drill a determined volume of rock (GJ/m^3). [5]

Rotary drilling rates of advance based on specific energy involves all types of energy consumed, such as energy of plastic deformation, friction, kinetic energy of chips, heat losses and energy of comminution. [9]

All drilling trials were carried out at two main rotary speeds, low speed (400 rpm) and high speed (1200 rpm).

Lengths of core produced from the testes are measured and time taken for the drilling is monitored so the penetration rate calculated is equal length of core per unit time. Note, the average penetration rates were estimated from the drilling trials at low and high speed for one and the same load.

The aim of this work is to study the effect of both operating parameters such as rotational speed, thrust and formation properties on the penetration rate in some sandstone rocks using diamond core bit.

PROPERTIES OF THE TESTED ROCKS:

Physical and mechanical properties such as density, porosity compressive strength, tensile strength and coefficient of friction are determined. Table (1) contains the average value for each property tested together with its standard deviation.

Table (1) Physical and mechanical properties of the tested rocks

Rock type	Density gr/cm3	Porosity %	Compressive strength, MPa	Tensile strength, MPa	Coeffi.Of friction
Sandstone A	2.02±0.009	23.84±0.695	110.96±9.33	24.99±1.79	0.70
Sandstone B	1.97±0.006	23.74±0.380	127.11±6.49	35.97±4.76	0.59
Sandstone C	2.034±0.007	18.85±0.180	142.70±6.85	35.97±1.29	0.66
Sandston D	2.003±0.016	21.38±0.707	139.92±5.84	25.18±1.99	0.83

Experimental work:

In the current research four types of the sandstone rocks were tested having various properties from different places in Aswan, Egypt were tested. Rocks prepared as blocks 20cm×15cm×15cm. Blocks tested in the laboratory by diamond bit with inside diameter 38 mm and outer diameter 40 mm.

All drilling trails were carried out at low speed equals 400 rpm and high speed equals 1200 rpm. Rotary speed in the tests measured by laser speedometer to monitors the applied speed. Water used as a drilling fluid for cooling the bit and remove the cutting.

The weight on bit is applied using loads which are suspended by a movable wheel by wire rope. The wheel is fixed into the machine gear axis. Hence the load is transferred into the bit. This transfer load is checked and measured using proving ring. Load on the drilling operations drilling tests have been conducted using drilling experiments and rock under tests were recorded.

Applied load, actual speed, length of borehole (length of core) and time of drilling are recorded as results of drilling in sandstone (D) as an example, and the average values of penetration rates are shown in table (2)

Table (2) Experimental data of S.S. (D) at 400 RPM

WOB, Kg	Length of core ,cm			Time, min.			Average PR cm/min	Average PR mm/sec
	Core 1	Core 2	Core 3	Time 1, min.	Time 2, min.	Time 3, min.		
18	14.5	14	13	2.2	2.3	1.9	6.58	1.1
24	9.5	11.5	12	1.35	1.73	1.85	6.63	1.11
30	11	12	13	1.55	1.70	1.8	7.11	1.19
36	12	12	14	1.48	1.64	1.6	8.34	1.39
45	14	12	8	1.21	0.62	0.51	15.48	2.58
60	7	9	5	0.73	0.38	0.25	21.74	3.58
75	13	13	10	0.73	0.75	0.53	17.94	2.99
90	13	13	10	0.71	0.65	0.45	20.38	3.4
105	14	14	11	0.73	0.50	0.51	20.04	3.34
120	14	14	10	0.67	0.50	0.43	22.0	3.67

RESULTS AND DISCUSSION:-

The following discussions show the relations between (WOB via PR), (WOB via Torque), (WOB via SE) and (PR via SE) at low and high speeds.
Table (3) shows PR, SE at 400 & 1200 RPM for different WOB in tested rocks.

Table (3) Data obtained of PR and SE at low and high speeds for different WOB

WOB, Kg	Rock A				Rock B				Rock C				Rock D			
	Low speed		high speed		Low speed		high speed		Low speed		high speed		Low speed		high speed	
	PR, mm/sec	S.E, MPa	PR	S.E	PR	S.E	PR	S.E	PR	S.E	PR	S.E	PR	S.E	PR	S.E
12	——	——	——	——	——	——	——	——	——	——	3.15	0.7	——	——	——	——
18	——	——	——	——	——	——	——	——	1.08	1.01	3.91	0.84	1.1	1.26	1.1	3.75
24	1.08	1.44	3.89	1.2	1.05	1.25	2.28	1.72	1.09	1.34	3.41	1.29	1.11	1.67	3.54	1.56
30	1.11	1.75	3.99	1.46	1.19	1.44	3.4	1.44	1.21	1.52	4.14	1.33	1.19	1.94	4.04	1.71
36	1.13	2.07	4.5	1.55	1.29	1.52	3.8	1.55	1.51	1.46	3.27	2.02	1.39	1.99	4.32	1.92
45	2.18	1.34	2.18	4.02	2.05	1.2	4.48	1.64	2.91	0.94	3.84	2.15	2.58	1.34	6.62	1.56
60	1.07	3.63	3.5	3.32	1.5	2.18	3.63	2.7	3	1.22	5.65	1.94	3.58	1.29	7.46	1.85
75	1.36	3.58	5.55	2.62	2.115	2.32	5.3	2.32	1.9	3.13	6	2.29	2.99	1.92	10.8	1.59
90	1.86	3.13	——	——	2.21	2.75	5.36	2.75	2.74	2.46	6.17	2.67	3.4	2.03	12	1.73
105	2.76	2.46	——	——	——	——	——	——	5.19	4.51	——	——	3.34	2.41	——	2.3
120	1.72	4.51	——	——	——	——	——	——	6.9	——	——	——	3.67	2.51	——	——

Figures (1,2,3,4) illustrate the relation between WOB and penetration rate at two rotary speeds 400 rpm and 1200 rpm.

The trend line for the results is that an increase WOB produces an increase in PR up to a maximum point. However, from the experimental data in table (3) a further increase in WOB causes constant or little increase in PR. The effect of rotational speed on PR of the bit is clear in the figures and data in table (3), an increase in rotary speed produced an increase in the PR. Relation between WOB and PR with correlation coefficients are given in Figs. (1), (2), (3), and (4). PR in rock (A) at WOB 105 kg was about 2.5 times that at 24 kg. There is also an increase in PR at rocks (B), (C) and (D) with increased WOB. PR in rocks (B), (C) and (D) at WOB 90,120 and 120 kg was about 2, 6 and 3 times that at 24, and 18 kg respectively in the low speed. In high speed PR in rock (A) at WOB 75 kg was about 1.4 times that at 24 kg. At WOB 90 kg in rocks (B), (C) and (D) PR increased abut 2, 2 and 10 times that at WOB 24, 12 and 18 kg respectively.

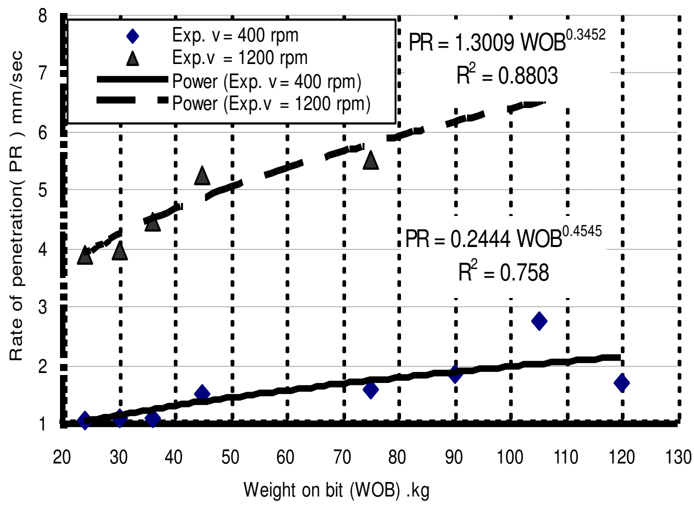

fig (1) Relation between WOB and PR for rock A in the high and low speed

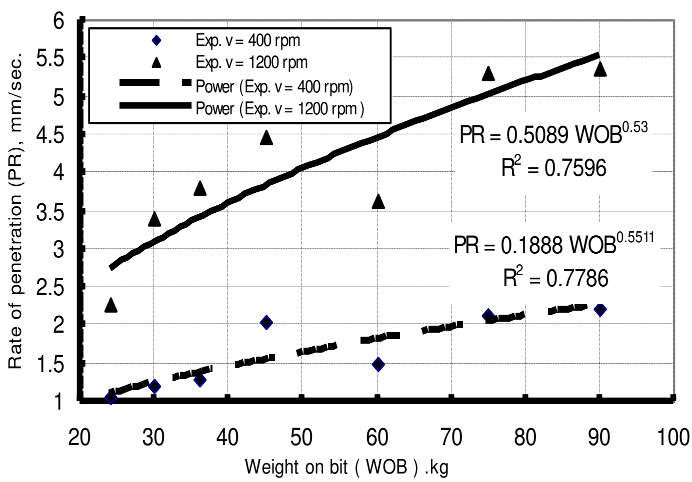

fig (2) Relation between WOB and PR for rock B in the high and low speed

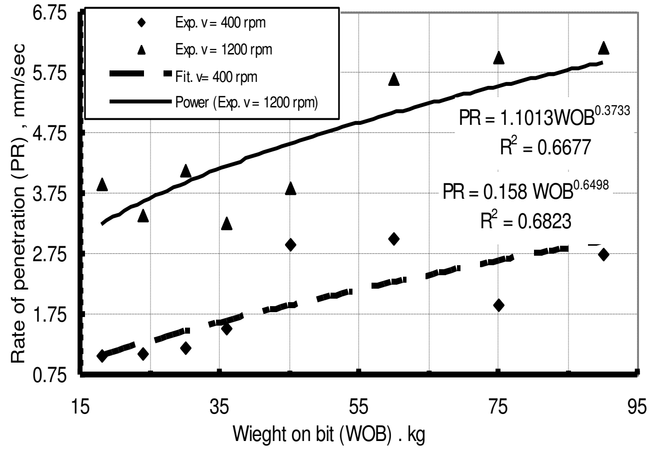

Fig.(3) Relation between WOB and ROP for rock C at high and low speed

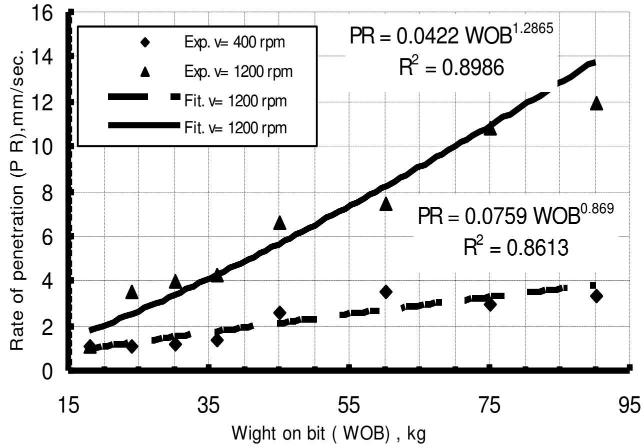

Fig.(4) Relation between WOB and ROP for rock D at high and low speed

2- Relations between WOB and Torque:

Torque is a force acts on a body to change its rate of rotation. It is the rotational equivalent of force in a linear motion system. Rotary torque is an indicator of what is happening at the drill bit and can be determined from the following equation [10].

$$T= \frac{2}{3}\mu F_v \frac{r_o^3 - r_i^3}{r_o^2 - r_i^2}$$

T = resisting torque, N.M F_V = applied thrust, KG.
r_o = outside radius , m r_i = inside radius , m μ = Coefficient of friction

Relationship between Torque and weight on bit is linear. The torque is found to be dependent on the weight on bit to the power of 1.1 according to field measurements. Table (4) gives the values of torque for the tested rocks which are calculated at different WOB. Relations between WOB and T are given in the figure (5) as an example; there is linear relation between WOB and T.

Torque value increases with increase in WOB in the four rocks. The following forms give the relations between WOB and T.

For sandstone A $T = 0.140\ WOB$
For sandstone B $T = 0.118\ WOB - 0.005$
For sandstone C $T = 0.132WOB - 0.001$
For sandstone D $T = 0.167\ WOB$

Table (4) Values of torque for the tested rocks at different WOB

WOB , KG	ROCK A	ROCK B	ROCK C	ROCK D
	Torque, Nm	Torque, Nm	Torque, Nm	Torque, Nm
18	——	——	2.39	3.01
24	3.38	2.85	3.19	4.01
30	4.23	3.56	3.98	5.01
36	5.07	4.27	4.78	6.01
45	6.34	5.34	5.98	7.52
60	8.45	7.12	7.97	10.02
75	10.57	8.91	9.96	12.53
90	12.68	10.69	11.95	15.03
105	14.79	——	13.95	17.54
120	16.9	——	15.94	20.05

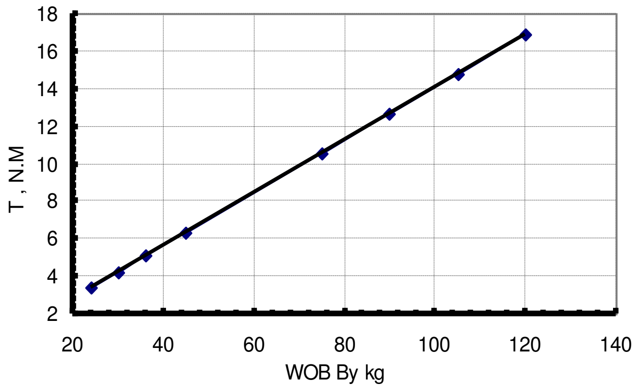

fig. (5) Relation betw een WOB and T in rock A

3- Relations between WOB and SE at low and high speeds:

Specific energy is directly related to the cost used to drill the hole, so the specific energy is the clear indication on the drilling performance in the rocks drilled in this study. Specific Energy (SE) can be defined as of the energy necessary to drill a determined volume of rock (GJ/m^3). [5]

$$SE = 2\pi * NT / A * PR$$

Where,

SE = specific energy; MPa.
N = rotary speed, rpm.
T = resistance torque, Nm.
A = area of the bit, mm^2.
PR = penetration rate. m/hr.

Specific energy values calculated from the above equation for all tests in high and low speeds, and values are illustrated in table (3).

The relations between WOB and SE, with correlation coefficients and are given in the figs. (6), (7), (8) and (9). In these figures increase in WOB produced an increase in SE for all rocks in low and high speed. The best values of SE which gave reasonable values of PR were 1.34, 1.20, 0.94 and 1.34 MPa at WOB 45 kg in rock (A), (B), (C) and (D) at 400 rpm respectively.

The minimum values of SE which give the reasonable values of PR were 1.20, 1.44 , 0.70 and 1.56 MPa at WOB 24 , 30 , 12 and 45 kg in rock (A), (B), (C) and (D) at 1200 rpm respectively .

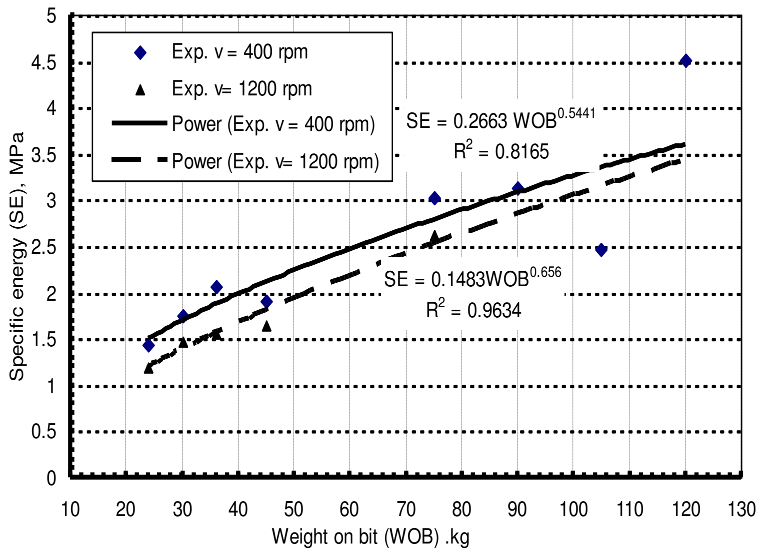

fig. (6) Relation between WOB and SE for S.S A at high and low speed

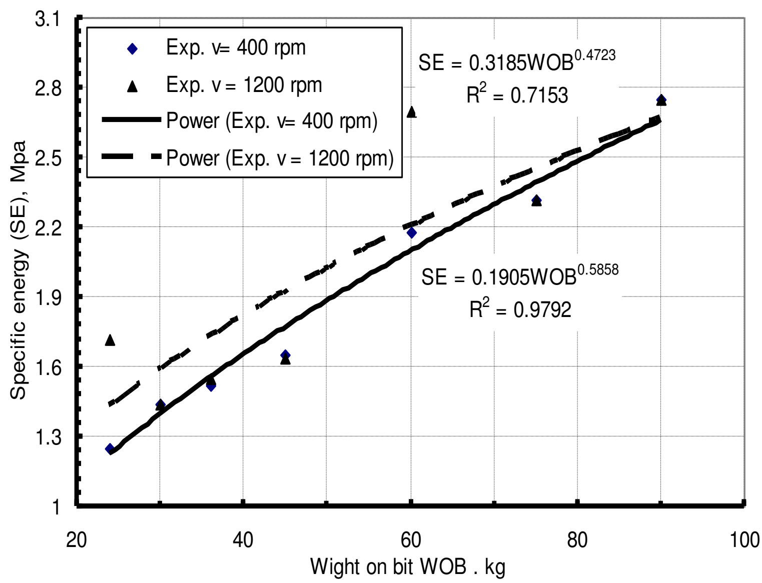

fig (7) Relation between WOB and SE for S.S B at low and high speed

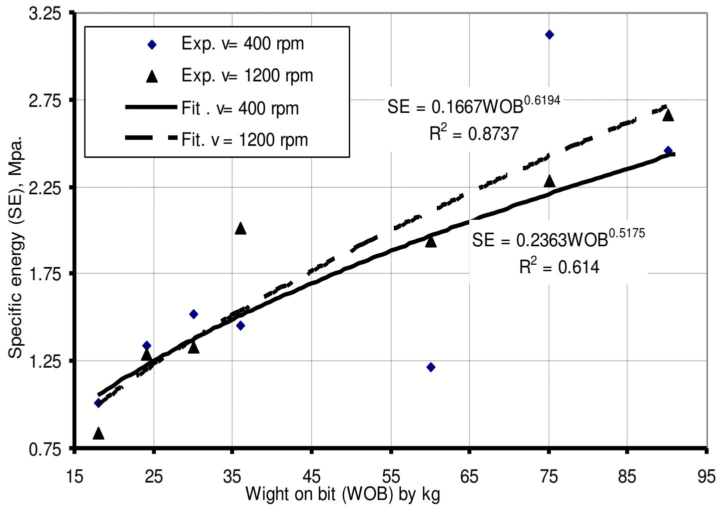

Fig.(8) Relation between WOB and SE for S.S C at high and low speed

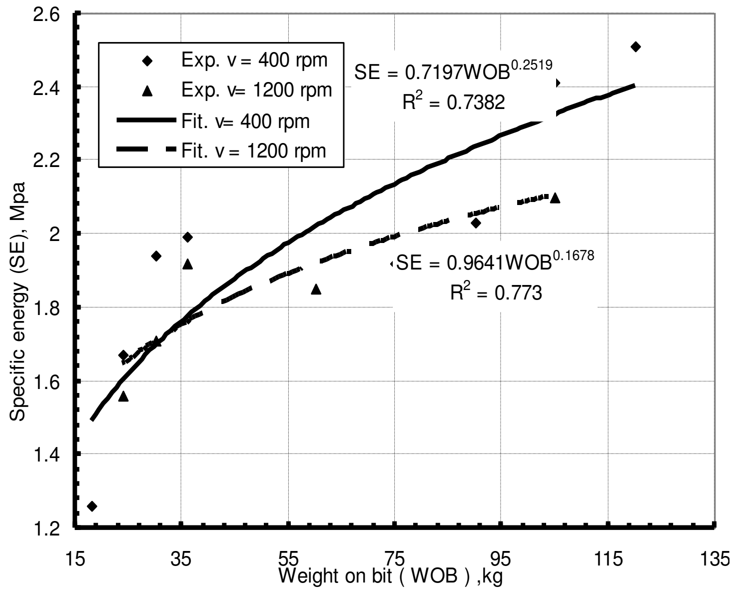

Fig.(9) Relation between WOB and SE for S.S D at high and low speed

4- Relations between PR and SE at low and high speeds:

Table (3) gives the different values of the SE and PR in the all rocks.

Figures (10), (11) give relations between PR and SE in sandstone (A) at low and high speed respectively. The SE increases with the increase in the PR to 3.63MPa, and with the increase of PR, SE decreases to 2.46 at low speed (400 rpm).The same trend happened at high speed (1200 rpm) as shown in Figs. (10), (11).

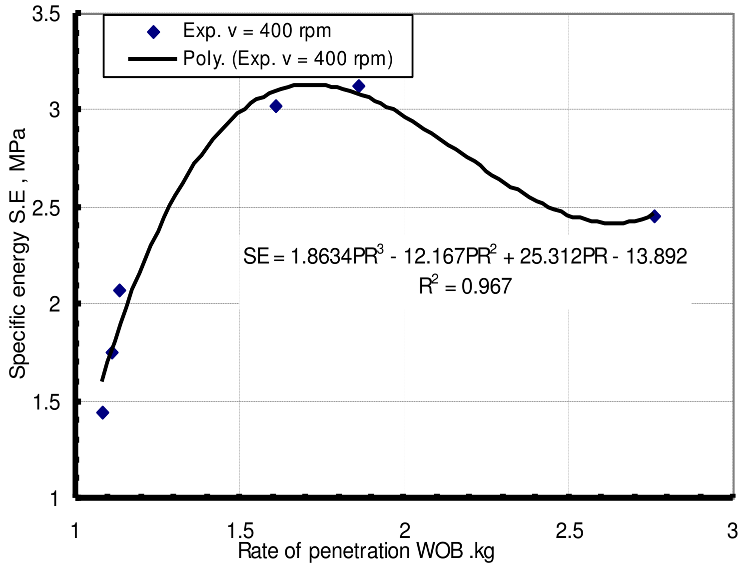

fig. (10) Relation between PR and S.E for rock A at low speed

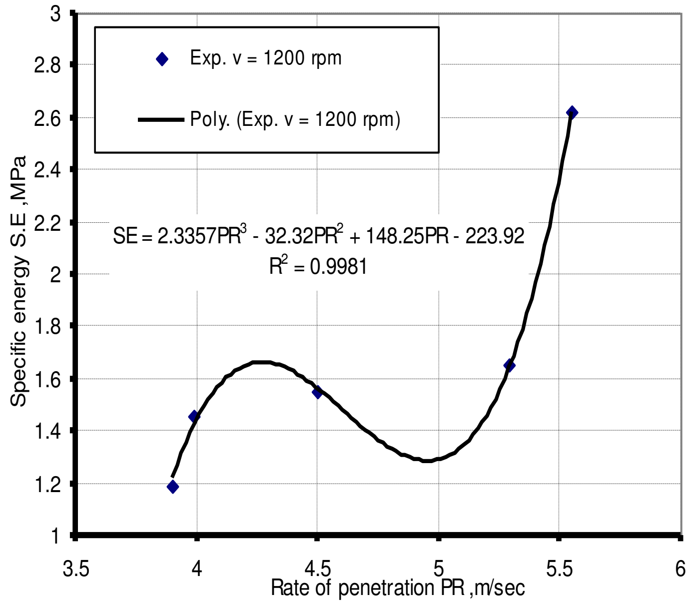

fig. (11)) Relation between PR and S.E for rock A at high speed

Figures (12), (13) illustrate the relations between PR and SE in the sandstone (B) at low and high speeds respectively. The SE decreases with the increase in PR at PR = 1.5 mm/sec, SE was at the min. value SE = 1.2 MPa and the SE increases with the increase in PR, and this may be due to the wear in the bit. The same trend happened at high speed (1200 rpm) as shown in Figs. (12), (13).

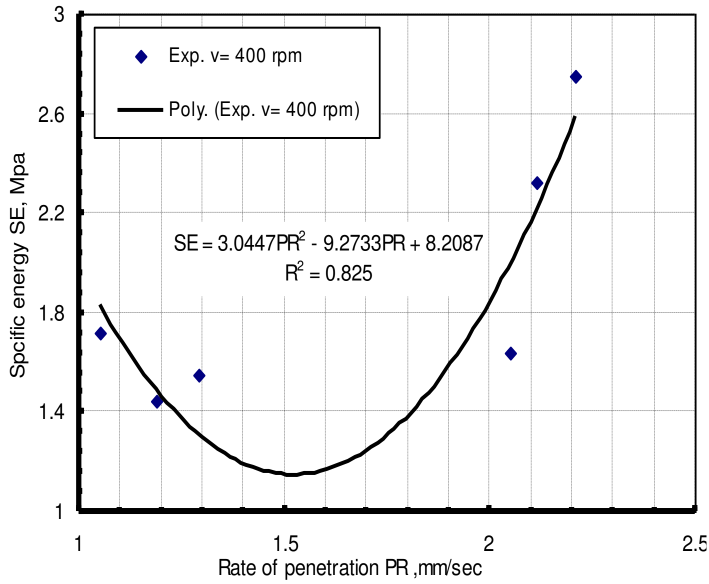

fig (12)Relation between PR and S.E for rock B at low speed

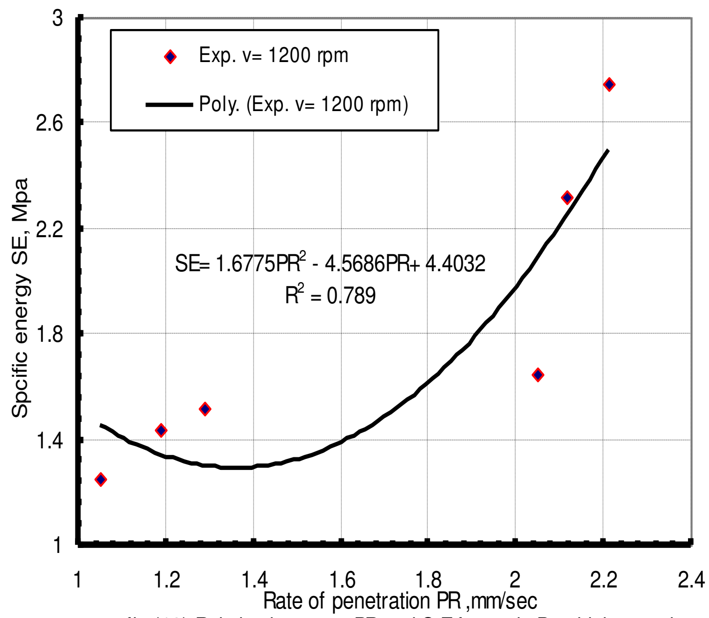

fig (13) Relation between PR and S.E for rock B at high speed

Figures (14), (15) illustrate relations between PR and SE in the sandstone (C) at low and high speed respectively. At low speed, the SE decreases with an increase in PR, at PR = 2.5 mm/sec, SE was at the min. value SE = 0.95 MPa and the SE increases with the increase in PR which may be due to the wear in the bit. In high speed SE decreases with an increase in PR, at PR = 4.75 mm/sec, SE was at the min. value SE = 1.5 MPa and the SE increases with the increase in PR.

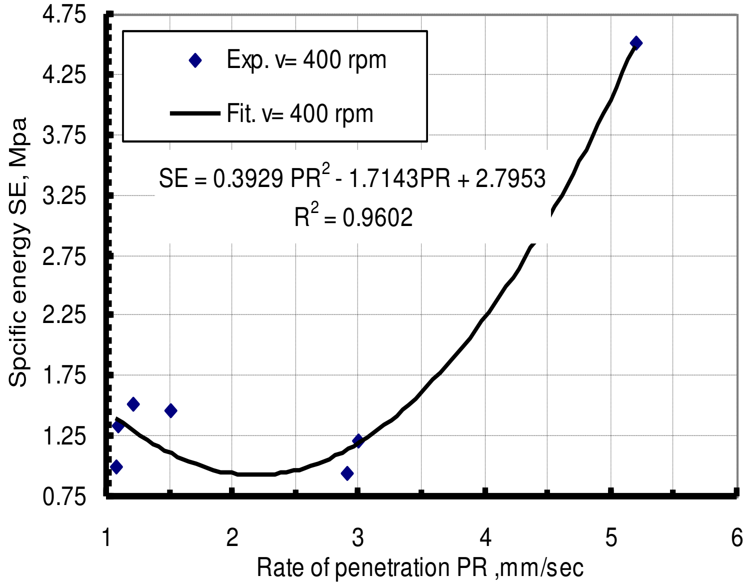

Fig.(14)) Relation betw een PR and S.E for rock C at low speed

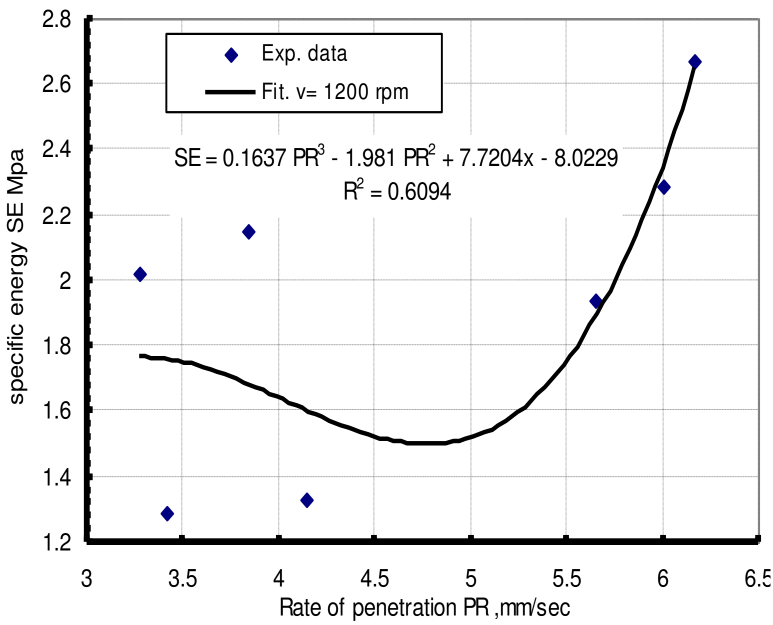

Fig.(15) Relation betw een PR and S.E for rock C at high speed

Figures (16), (17) illustrate the relations between PR and SE in the sandstone D at low and high speed respectively. SE increases with an increase in PR at the two speeds (400, 1200 rpm), this is because the used bit appears to be at the end of its life.

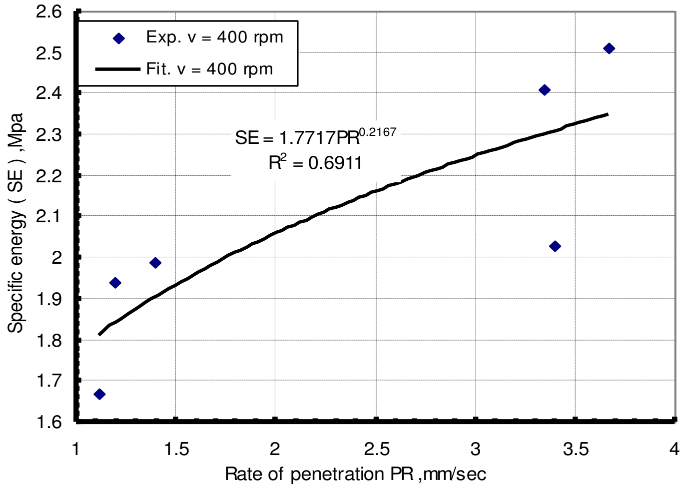

Fig.(16)) Relation betw een PR and S.E for rock D at low speed

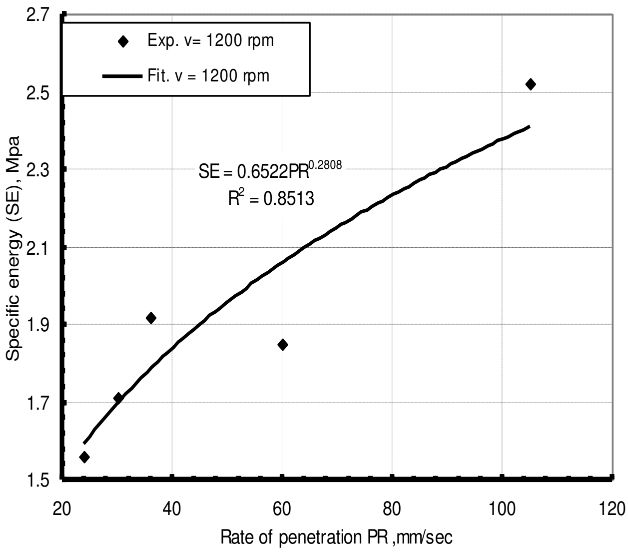

Fig.(17) Relation betw een PR and S.E for rock D at high speed

CONCLUSION

- Four sandstone rocks were drilled by diamond core bit using a fixed laboratory drilling machine with two speeds at low speed 400 rpm and high speed 1200 rpm , the range of the weight on bit applied started from 12 to 120 kg.
- Relations between WOB and both PR, T, and SE were given, relation between PR and SE were also given. From experimental data drilling performance is dependant on operating parameters especially rotary speed and WOB. Mathematical equations between parameters are given from trend line on the curves.
- In low speed the increase of WOB causes an increase in PR. In rock (A) at maximum WOB 105 PR was about 2.5 times that at minimum WOB 24 kg. PR

increase in rocks (B), (C) and (D) with increase WOB, at WOB 90, 120 and 120 kg the increase in PR was about 2, 6 and 3 times that at 24, 18 and 18 kg respectively.

- The high speed increase in WOB produces an increase in PR, penetration rate in rock (A) at maximum WOB 75 kg was about 1.4 times that at 24 kg. At WOB 90 kg in rocks (B), (C) and (D) PR increased about 2, 2 and 10 times that at WOB at 24, 12 and 18 kg respectively.
- Penetration rate at high speed is more than that at low speed in a specific load. At WOB 90 kg as an example PR at high speed were about 3.1, 2.4, 1.9 and 3.5 times the PR at low speed in rocks (A), (B), (C) and (D) respectively.
- Increase in WOB produced an increase in SE for all rocks in low and high speed. The best values of SE which give reasonable values of PR were 1.34, 1.20, 0.94 and 1.34 MPa at WOB 45 kg in rocks (A), (B), (C) and (D) at 400 rpm respectively.
- The minimum values of SE which give the reasonable values of PR were 1.20, 1.44 , 0.70 and 1.56 MPa at WOB 24 , 30 , 12 and 45 kg in rocks (A), (B), (C) and (D) at 1200 rpm respectively .
- The quartz content as well as other intercalations in sandstone cause high wear in the bit used in drilling and cause also the differences in the relations between PR and SE which are clear from the curves and experimental data.

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تأثير عوامل التشغيل وخواص التكوينات الصخرية علي معدل الاختراق في بعض صخور الحجر الرملي باستخدام بنطة حفر مطعمة بالماس

في هذه الدراسة تم الحفر في أربعة أنواع من صخور الحجر الرملي باستخدام ماكينة حفر معملية ثابتة عند سرعتين 400 و 1200 لفة في الدقيقة وتطبيق أحمال مختلفة تتراوح بين 12و 18و24و 30 و........150 كجم. عوامل التشغيل في الحفر هي الحمل المطبق على البنطة و معدل الاختراق و عزم الدوران والطاقة المبذولة .تسجل هذه العوامل باستمرار أثناء عملية الحفر بجانب تأثير خواص التكوينات الصخرية على معدل الاختراق . تم استنتاج العلاقة بين الحمل المطبق على البنطة وكل من معدل الاختراق وعزم الدوران وكمية الطاقة المبذولة. وكذلك العلاقة بين معدل الاختراق والطاقة المبذولة تم استنتاجها. وفى النهاية تم رسم المنحنيات بين الحمل الواقع علي البنطة و كل من المتغيرات السابقة . ومن خلال هذه المنحنيات والمعادلات الرياضية يمكن أن نتوقع أداء وكفاءة عملية الحفر بسرعة سهولة .