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THE APPLICATION OF PDC PINS IN ROCK CORING BITS

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ABSTRACT: Since the introduction of polycrystalline diamond compact (PDC) bits in the mid-1970's, their applications in the Mining and Oil industries have significantly advanced drilling technology. The drilling performance of these bits is influenced by a range of factors, however, the principal factors which need to be considered in predicting drilling rates are the bit, the bit operating parameters and the characteristics of the penetrated rock. A variety of rock types were drilled using two types of PDC and impregnated diamond core bits using a fully instrumented laboratory drilling rig at different rotational speeds and over a range of weights on bit. A wide range of mineralogical, textural, mechanical and intact properties of the rocks were quantitatively determined. The effects of the operating parameters and penetrated rock characteristics on the performance of the bits were examined Comparisons of the optimum performance were made between the PDC and an impregnated diamond core bit.

1 INTRODUCTION

Developments in polycrystalline diamond compact (PDC) production techniques have enabled the manufacture of a rectangular "pins" of material which have been incorporated into various forms of core bits. Although PDC have existed for more than 40 years, the material and its applications are still being developed. Unfortunately, early and possibly injudicious trials during its development led to much adverse pre-judgement and prejudice. Much of this adverse reputation has been founded upon ignorance of the proper use of PDC and the necessary expertise required to get the best from it. Thus, earlier PDC applications and bit design (between 1954-1970) generally experienced poor and uneconomical results. Real advances in drilling efficiency were achieved in the early 1980s. Since then, PDC bits have been economically employed for soft, medium hard and abrasive formations in oil field and mining applications.

PDC bit designs have been reviewed by Feenstra (1988). Among other topics that have received attention are wear mechanism and self sharpening effect (Glowka and Stone, 1985; Glowka, 1989; Sinor and Warren, 1989; Brett et al., 1990; Wojtanowicz and Kuru, 1993), rock cutting (Cheatham and Daniels, 1979, Swenson et al., 1981; Zijsling, 1987; Glowka, 1989), drilling action of the bit (Detoumay and Defourny, 1992), bit performance (Black et al., 1986; Warren and Armogost, 1986; Warren and Sinor, 1989; Glowka, 1989). All of these refer to PDC non-core bits and most were concerned with a single cutter-However, little attention has been given to the effects of the operating parameters and a wide range of rock characteristics on the performance of PDC core bits.

Drilling tests both in the field and in the laboratory are indispensable in evaluating the performance of specific bit designs, to facilitate operating parameter determination and selection of appropriate bits for particular applications. The overall performance of any drill bit is complex and is effected by numerous factors which include the operating parameters of the bit, the rock properties, the bit type and design, wear characteristics, drilling fluid properties and flow mechanics, hole characteristics, capacity of the drilling machine, accuracy of the monitoring system, time, climate and operator or crew efficiency However, the principal factors which require consideration in predicting drilling rates are the operating parameters of the bits and the characteristics of the penetrated rock These factors are examined in this paper together with comparisons of the optimum performance of the bits under similar drilling conditions in different rock types

2. CORE BITS TESTING

The variety of diamond bits available for rock drilling has increased considerably in the past few years with the introduction of new PDC pin products Three types of core bits are now produced natural surface set bits, impregnated synthetic diamond bits, and bits set with synthetic PDC pads or pin inserts. Each type includes variations in face geometry, matrix composition, diamond or PDC size and shape, and optimal operating conditions.

In this study, drilling trials were conducted in limestone, siltstone, sandstone, granite and diorite using PDC and impregnated diamond BQ (ID 36mm, OD 59mm), wireline, core bits, as illustrated in Figure 1, on a fully instrumented laboratory drilling rig. Two types of PDC bits, pin and hybrid, based on the "Syndax3" product were tested Syndax3 is a solid, unbacked, polycrystalline diamond product, which is thermally stable to 1200 °C in a reducing atmosphere (Tomlinson and Clark, 1992). The PDC bit crown consists of two components, matrix and cutter. In conventional PDC bits, matrix is mainly made up from tungsten carbide-cobalt (WC-Co) Many cobalt based PDC products progressively degrade when heated to 750°C or above, due to the presence of a residual solvent/catalyst. There was no cobalt used in the PDC bits in this study, instead a ceramic (mainly silicon carbide) secondary phase was used, which is chemically inert and has a similar coefficient of thermal expansion to that of diamond In addition, there is no substrate to introduce problems of differential thermal expansion. The matrix also contained small amounts of Cu, Ni, Zn, Fe and Mn The cutting material was made of polycrystalline diamonds in the form of a rectangular bar of approximately 2 mm section. Syndax3 pin bits are manufactured by the infiltration route, using the same techniques as for other PDC products. Shallow holes are drilled into the graphite base plate in the selected pattern setting and the pins simply glued into position vertically. Several pins are usually positioned for gauge maintenance, reinforced by additional carbide wear strips and natural diamond kicker stones. The number of pins used in a bit and pattern setting design will depend on the formation for which it is intended. From the drilling trials, it has been experienced that a PDC core bit that contains fewer pins should be used for hard rock drilling, and a bit which contains more pins is used for soft and abrasive rock drilling. The pin bits used had a total of six segments and each segment contained eight Syndax3 pins and 5 or 2 carbide strips which were symmetrically placed around the outside and inside edges

The hybrid bit is essentially an impregnated bit enhanced with Syndax3 PDC pins This concept was termed "hybrid" to identify the duality of the cutting structure. As the pins extend the full depth of the impregnated matrix, the normal serrated face profile can be maintained which has the advantage of providing an aggressive drilling action with good directional stability However, in conventional bits the serrated profile is lost in very hard formations due to wear of the bit face As the hybrid bit enters harder formations wear of the PDC brings impregnated diamond particles into contact with the formation. Support of the PDC pins with the impregnated diamond matrix can also enable greater weight on bit to be run with a reduced chance of cutter breakage due to the cutter overloading. The hybrid bit has six or eight segments and each segment contains four Syndax3 pins Matrix impregnation of the hybrid bit utilised synthetic diamonds with a blocky and cubo-octahedral shape of 30-40 US mesh (~ 600um in diameter) at 40 concentration.

The impregnated bit also had eight segments. It was manufactured using a soft matrix material, SDA 100 synthetic diamonds of 30-40 US-mesh (~ 600um in diameter), at 40 concentration. The synthetic diamonds were uniformly distributed through the matrix of the bit. All bits had six or eight 3 mm wide waterways which were symmetrically placed. Materials and design characteristics of the bits are given in more detail elsewhere (Ersoy, 1995)

The operating parameters of the drill bits, rate of penetration (ROP), weight on bit (WOB), rotational speed (RPM), torque and drilling specific energy (SE) were monitored on a computer controlled logging system. Water was used as flushing medium and the flush flow rate was held constant at 601/min during all the drilling trials. The WOB and RPM are considered independent variables, whereas the other parameters are considered to be dependent variables determined by the bit type, rock type and rotational speed. Each rock was drilled using each bit over a range of WOB and at three different nominal rotational speed (550 rpm, 1150 rpm and 1650 rpm).

These speeds reduced over a small range with increasing torque Therefore, for each bit a range of drilling data is given for each rock, at each different RPM and applied WOB Full results obtained from drilling trials are given elsewhere (Ersoy, 1995)

3 ROCK PROPERTIES

Any analysis of bit performance must include consideration of the properties of the rocks Rock drillability or cutability cannot be defined by a single index or measured by a single test since there is no single rock parameter which can adequately define the breakage characteristics that predominate in a variety of different drilling techniques A wide range of laboratory tests including mineralogical, textural, chemical, physical and index properties analysis have been conducted on the drilled rocks

Mineral type and content were determined from rock thin sections The textural characteristics are grain, size, grain shape, degree of grain interlocking, grain orientation, relative proportions of grains and matrix These were quantitatively measured using an automatic image analysis system and used to derive a texture coefficient (TC), which models the interaction between the rock texture and the drill bit, as a single number Total silica content was determined using X-ray fluorescence The mechanical properties measured were, uniaxial compressive strength (UCS), indirect tensile strength (BTS) and Young's Modulus which were determined according to ISRM suggested methods (Brown, 1981) Index tests included overall Moh's rock hardness and Shore Schleroscope hardness number, Cerchar abrasivity index, dynamic impact abrasive index (DIAI AI-Ameen and Waller, 1992) and Schimazek's F-abrasivity factor (Schmazek and Knatz, 1970) These characteristics are presented in Tables 1 -3 Note that methodology, procedure and equipment used for the above tests together with detailed rock description are given elsewhere (Ersoy 1995)

Table 1 Textural and mineralogical properties of the rocks

Rock types	Texture coeff	Grain size (mm)	Grain shape factor	Quartz content (%)	Silica content (%)
Limestone	144	0 744	0 512	0	0 00
Sandstone	126	0 410	0 597	83	91 22
Siltstone	0 47	0 085	0 677	59	81 62
Granite	2 27	0 703	0 468	34	72 38
Dionte	2 45	0 241	0 480	0	51 57

Table 2 Mechanica properties of the rocks

Rock types	UCS (MPa)	BTS (MPa)	Young mod (GPa)	Density (gm/cm^3)
Limestone	28 17	2 86	9 74	2 23
Sandstone	37 45	3 21	9 85	2 27
Siltstone	90 54	7 49	17 70	2 39
Granite	10615	8 60	19 78	2 61
Diorite	375 20	30 26	37 38	2 99

Table 3 Intact properties of the rocks

Rock types	Moh's hard-ness	Shore hard-ness	Cerchar abr ind	DIAI (%)	F-abr factor (N/mm)
Limestone	2 85	19	0 63	150	0 06
Sandstone	6 44	41	3 83	68 39	1 13
Siltstone	5 51	51	170	44 23	0 41
Granite	5 74	85	3 75	70 76	3 02
Diorite	5 95	95	3 31	72 41	2 48

4 INFLUENCE OF DRILLING VARIABLES ON THE DRILLING PERFORMANCE

The optimum data for the bits were extracted from each series of results using a criteria based on maximum ROP at minimum drilling SE or vice versa SE gives a very good indication of bit performance This is illustrated in Figures 2 and 3 which show the WOB and SE versus ROP for the PDC bits in limestone at 1650 RPM The regions of the SE and WOB curves selected as optimum performance are shown between vertical delimiters These figures show clearly that high ROP is produced at low SE The optimum data were used for performance comparisons of the bits and in the correlation matrix of operating parameters and rock properties Figures 2 and 3 also show that increasing WOB gave increasing ROP up to some maximum point Further increase of WOB causes constant or little increases or, in some cases, a decreases ROP Generally at low WOB, SE increases, at optimum WOB, the SE minimises, and at high WOB it increases again However, SE is more dependent on the ROP and rock characteristics (textural and mechanical) than on WOB and other parameters There were some fluctuations in ROP with increasing WOB, especially when drilling the hard rocks The reductions in ROP with increasing WOB were due to inadequate pin exposure and the development of wear flats All the bits showed an increase in the penetration rate per revolution at a given WOB with decreasing rotational speed There is a linear relationship between torque and WOB up to the point of maximum ROP, any further increase causes no increase in rock fragmentation but may increase friction losses.

The effects of the drilling variables on ROP are represented in Figures 4 to 10. A full set of graphs can be .found in Ersoy (1995). The effects of RPM and WOB on the ROP are illustrated in Figures 4 to 6. From examination of these, and other graphs, the following points were observed.

1. ROP rises both with increasing RPM and WOB. However, the majority results suggest that the best ROP was gained at 1150 rpm except for sandstone and where new bits were used in the other rocks.

2. When RPM is increased a given ROP could be obtained at a lower WOB. The increase in RPM is limited up to the capacity of the drilling machine. Increasing RPM and WOB results in increasing ROP.

3. As the RPM was increased the WOB required to sustain a given penetration per revolution increased. A particular ROP can be obtained with lower WOB by increasing RPM. A considerable reduction in torque was found at the higher speed.

4. When the bit inserts were sharp especially after drilling abrasive rocks, the WOB at a given ROP, was reduced at higher RPM.

The PDC bits maintain their sharpness longer than the impregnated bit under similar conditions. Severe wear of the impregnated bit occurred in sandstone at higher speeds.

Examples of the relationship between torque, WOB and ROP for the impregnated bit in limestone and the hybrid bit in diorite are shown in Figures 7 and 8. These Figures, and other data, show torque as independent of ROP. Torque is more dependent on RPM and WOB. Increasing WOB tends to result in reducing RPM, although the penetration per revolution increases the overall ROP remains little changed due to the reduction in RPM.

Figures 9 and 10 show the relationship of SE to the performance of the PDC bits in limestone. There are two main trends apparent from the examination of SE-ROP-WOB surface graphs. Firstly, the pin and hybrid bits in siltstone, the pin bit in sandstone, the pin and impregnated bits in diorite, granite and limestone show high ROP at low SE. Many graphs also show an optimum WOB for maximum ROP at minimum (or low values of) SE. Secondly, the highest ROP values lie along a ridge of SE. Then, the ROP varies with WOB showing a definite "peak" at particular values of WOB. It should be noted that in Figure 10, a ridge is significant and the 350 MPa axis line corresponds to a previously used hybrid bit which, although drilling at a lower ROP, gave lower SE. The ridge data obtained from a new bit gave a higher ROP but operated at a higher SE.

5. INFLUENCE OF ROCK CHARACTERISTICS ON THE DRILLING PERFORMANCE

Statistical correlation matrices of the drilling variables (ROP, WOB, RPM, Torque and SE) with the tested rock properties were used in the data analysis. The optimum data were used for the operating parameters. The tables suggested that many of the rock properties used in this study had a high degree of correlation for a given rock type.

For the pin bit there was a good correlation of ROP with quartz content, Brazilian tensile strength (BTS), Young's Modulus and Shore hardness and a moderate correlation with grain shape factor, texture coefficient (TC) and uniaxial compressive strength (UCS). A strong correlation existed between WOB, UCS, BTS, Young's Modulus and Shore hardness.

For the hybrid bit there was strong correlation of ROP with silica content and good correlation with TC, grain shape factor, quartz content, UCS, BTS, Young's Modulus and Shore hardness. A strong correlation was also observed between WOB and quartz content, UCS, BTS, Young's Modulus and Shore hardness.

For the impregnated bit there was strong correlation of ROP with shore hardness and Young's Modulus and moderate correlation with TC, quartz content, UCS, BTS and F-abrasivity factor. A good relationship was found between WOB and Shore hardness and F-abrasivity factor.

Texture coefficient has a positive influence over drilling performance since an interlocked texture presents a physical barrier to crack propagation. Consequently ROP is significantly effected by TC. This, together with Shore hardness, quartz content, BTS, UCS, Young Modulus and grain shape were dominant in the correlation matrix. The Shore hardness measurement encompasses all grain characteristics, degree of cementation or crystallisation, bonding structure and intact characteristics of the rocks. Quartz is an abrasive and hard mineral which makes a major contribution to the wear of the bits. Also the pressure exerted by the cutters must exceed the strength (UCS, BTS) of the rock for the bit to be able to cut the formation efficiently. Because of the interlocking, angular, elongated and rough rock particles produce lower ROP and higher wear rate than rocks with rounded particles. The grain shape varies from close to zero for very elongated and angular particles to one for perfectly round particles

6 OPTIMUM BIT PERFORMANCE

Figures 11 through 13 show the optimum bit performances in the various rock types at 550, 1150 and 1650 rpm respectively. From the Figures, the following points can be summarised.

1 PDC pin bits generally show an excellent performance in soft to medium-hard formations, however, the impregnated bit gave slightly better performance in hard rocks The pin bit became polished more quickly than the impregnated bit in these rocks A new pin bit was used in granite and diorite A new hybrid bit was also used in granite at 1650 rpm Therefore these bits show higher performance than the impregnated bit in these rocks

2 The impregnated diamond bit wore rapidly in siltstone and excessively in sandstone at all speeds when compared to the PDC bits However the soft matrix of the impregnated bit was not suited to the highly abrasive rocks A harder matrix bit would have given better wear resistance The wear characteristics of all the bits are given elsewhere (Ersoy and Waller, 1995)

3 The impregnated diamond bit showed better performance in limestone than the PDC bits at 550 rpm, it also had slightly higher performance in limestone than the hybrid bit at 1150 rpm (Figures 11 and 12) The Limestone was tested with an impregnated bit which had previously been used to drill the abrasive siltstone This would have left the bit with good diamond exposure giving good drilling performance

4 PDC hybrid bit did not perform as well as the pin and impregnated bits in hard rocks except for the tests in granite at 1650 rpm, where a new hybrid bit was used

5 The best overall drilling and wear performance for all bits and rocks was obtained at 1150 rpm The corresponding linear cutter speed may be taken as a guide for field drilling

7 CONCLUSIONS

Knowledge of the rock properties is essential for the proper design of the bit and drilling machine, and for the selection of their operating conditions It is necessary to able to conduct drilling tests in a wide range of rock types because the resistance of rock to drilling depends to large extent upon the rock properties and the means used for cutting. Thus a wide range of rock characteristics were quantitatively determined Shore hardness, quartz and silica content, BTS, UCS, Young's Modulus, TC and grain shape factor were found to have a significant effect on ROP of the bits. Many of the rock properties used in this study were also found to have high degree of correlation for a given rock type

The bit performances are significantly effected by the drilling variables such as WOB, RPM, torque and SE The PDC pin and hybrid bits produced excellent performances in soft and medium hard rocks These bits also exhibited excellent wear resistance However, the impregnated diamond bit demonstrated slightly better performance in hard rocks than PDC bits but suffered high wear in abrasive rocks. However, the soft matrix of the impregnated bit was not suited to the highly abrasive rocks.

REFERENCES

Al-Ameen, SI and Waller, M D, 1992 Dynamic Impact Abrasion Index for rocks *Int. J. Rock Meek Mm. Sei. and Geomec. Abstr* 29 (6). 555-560

Black, A, Walker, B, Tibbitts, G. and Sandstrom, J, 1986 PDC bit performance for rotary, mud motor, and turbine drilling applications *SPE Drilling Engineering* 409-416

Brett, J F , Warren, T M and Behr, S M, 1990 Bit whirl-a new theory of PDC failure *SPE Drilling Engineering* 5 275-281

Brown, E T , 1981 *Rock characterisation testing and monitoring 1SRM suggested methods* London Pergamon

Cheatham, J J B and Daniels, W A, 1979 Study of factors influencing the drillabilty of shales single cutter experiments with stratapax drill blanks *J. Ener. Res Tech* 101

Detournay, E and Defourny, P A, 1992 Phenomenological model for the drilling action of drag bits, *hit J. Rock Mec Mm. Sei. and Geomec. Abstr* 29 13-23

Ersoy, A, 1995 Performance analysis of polycrystalline diamond compact (PDC) core bits in rocks *Ph.D. Thesis in preparation.* University of Nottingham

Ersoy, A and Waller, M D , 1995 Textural characterisation of rocks *Engng. Geo/* (Accepted for publication)

Ersoy, A and Waller, M D, 1995 Wear

characteristics of PDC pin and hybrid core bits in rock drilling. *Wear.* (Accepted for publication).

Ersoy, A., Waller, M.D. and Clark, I., 1995. The influence of rock properties on polycrystalline diamond compact (PDC) drill bits performance. *Ind. Diam. Rev.* (Accepted for Publication).

Ersoy, A. and Waller M.D, 1995. Drill bit performance prediction using multi-variable linear regression analysis. *Trans. Inst. Min. Metall. Section A.* (Accepted for publication in May-Aug).

Ersoy, A. and Waller, MD., 1995. Performance analysis of polycrystalline diamond compact (PDC) core bits. *geoDrilling* (Accepted for publication).

Feenstra, R., 1988. Status of porycrystaUine-diamond-compact bits: part 1-development. *J. Petrol. Tech.* June: 675-684.

Feenstra, R., 1988. Status of polycrystalline-diamond-compact bits: part 2-applications. *J. Petrol. Tech.* (July): 817-821.

Glowka, DA and Stone, CM., 1985. Thermal response of polycrystalline diamond compact cutters under simulated downhole conditions. *SPE J.* April: 143-156. —

Glowka, D A, 1989. Use of single cutter data in the analysis of PDC bit designs: part 2-development of and use of the PDC wear computer code. *J. Petrol. Tech.* 41: 850-859

Schimazek, J. and Knatz, H., 1970. The influence of rock structure on the cutting speed and pick wear of heading machines. *Gluckauf.* 106: 274-278.

Sinor, A. and Warren, T.M., 1989. Drag bit model. *SPE Drilling Engineering* 4: 128-136.

Swenson, D., Wesenberg, D. and Jones, A, 1981. Analytical and experimental investigations of rock cutting using polycrystalline diamond compact drag cutters. In *SPE 10150 Proc. 56 th Arm. Tech. Con/. Exhibit.*

Tomlinson, P.N. and Clark, I.E., 1992. Syndax3 pins-new concepts in PDC drilling. *Ind. Diam. Rev.* 52:109-114.

Warren, T.M. and Sinor, A, 1989. Drag bit performance modelling. *SPE Drilling Engineering* 4: 119-127.

Warren, T.M. and Armogost, W.K. 1986. Laboratory drilling performance of PDC bits. In *SPE 15617 Ann. Tech. Conf.* New Orleans.

Wojtanowicz, A.K. and Kurjv E., 1993. Mathematical modelling of PDCbit drilling process based on a single-cutter mechanics. *J. Energy Res. Tech.* 115:247-256

Zijsling, D., 1987. Single cutter testing-a key for PDC bit development. *SPE 16529 In Proc. Offshore Europe 87.* Aberdeen.

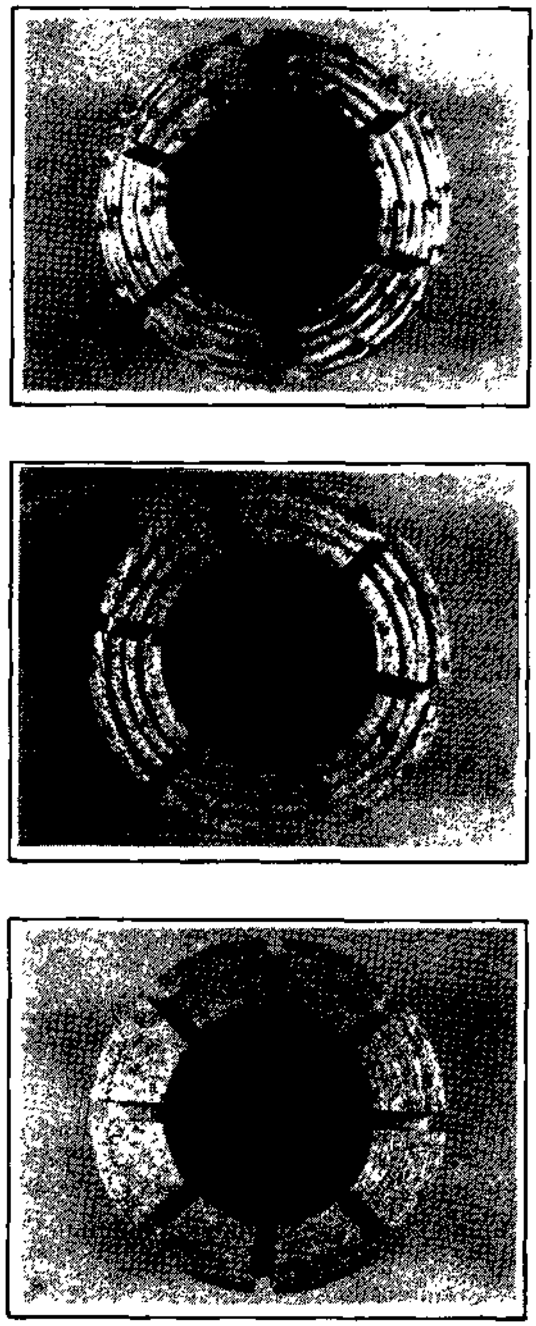

Figure 1. Illustrations of; top, pin bit, middle hybrid bit; bottom, impregnated bit.

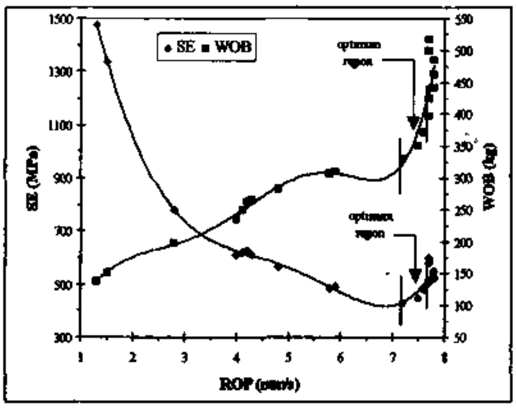

Figure 2 ROP versus WOB and SE for pin bit in limestone at 1650 rpm

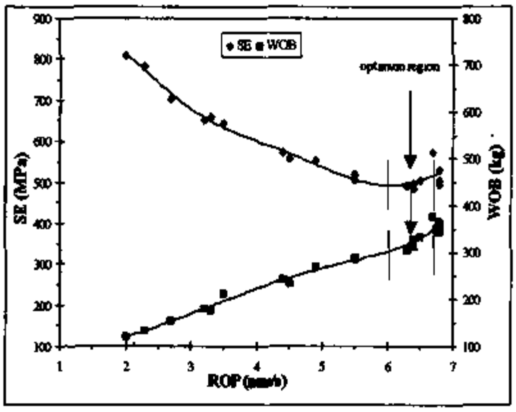

Figure 3 ROP versus WOB and SE for hybrid bit in limestone at 16S0 rpm.

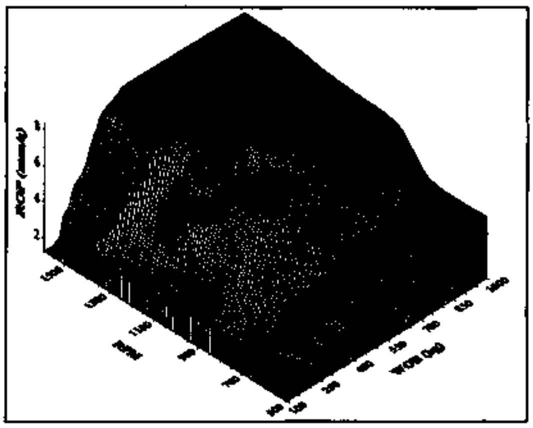

Figure 4 Three dimensional graph of WOB, RPM and ROP for the pin bit in limestone

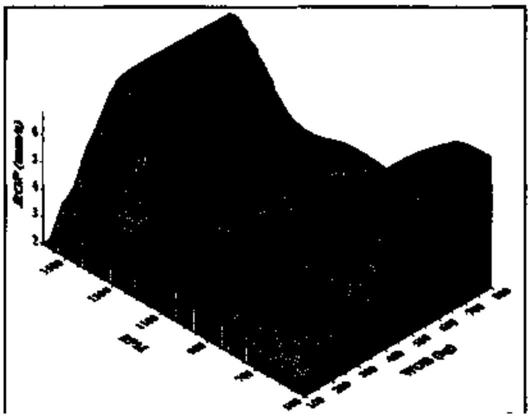

Figure 5 Three dimensional graph of WOB, RPM and ROP for the hybrid bit in limestone

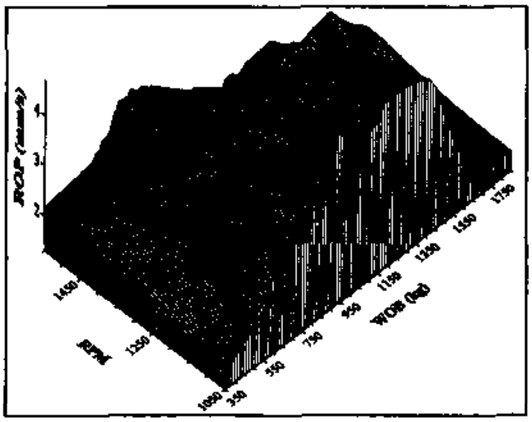

Figure 6 Three dimensional graph of WOB, RPM and ROP for the impregnated bit in diorite

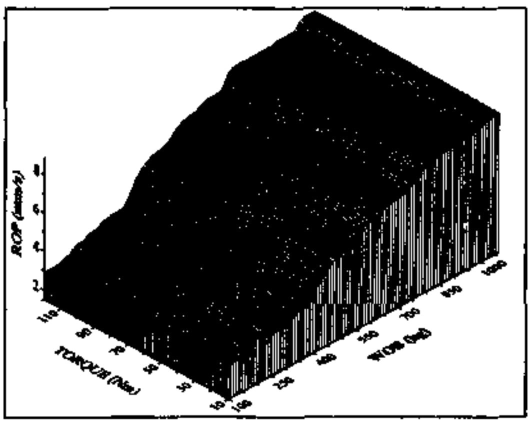

Figure 7 Three dimensional graph of WOB, Torque and ROP for the impregnated bit in limestone

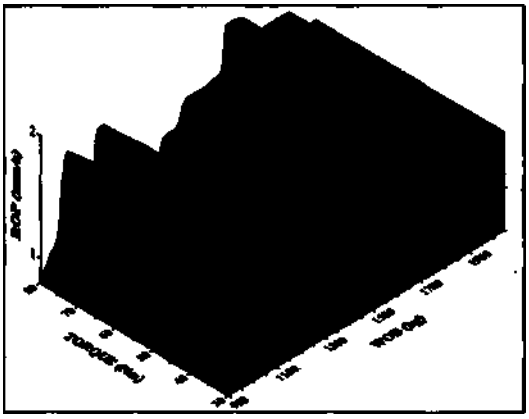

Figure 8. Three dimensional graph of WOB, Torque and ROP for hybrid bit in diorite.

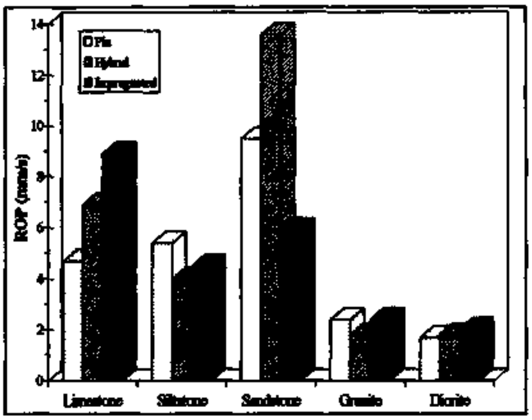

Figure 11. The optimum performances of the bits in rock types at 550 rpm.

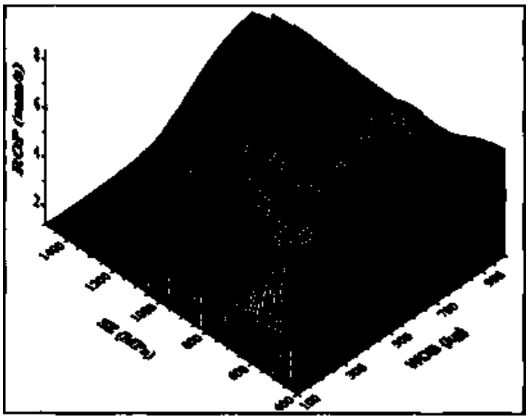

Figure 9. Three dimensional graph of WOB, SE and ROP for the pin bit in limestone

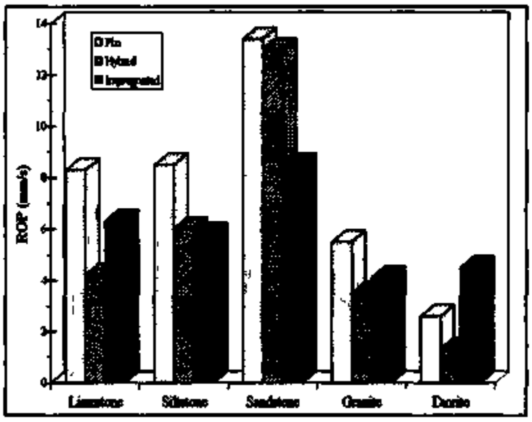

Figure 12 The optimum performances of the bits in rock types at 1150 rpm.

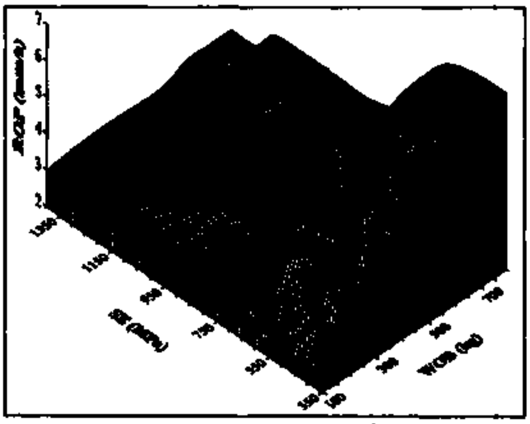

Figure 10. Three dimensional graph of WOB, SE and ROP for the hybrid bit in limestone.

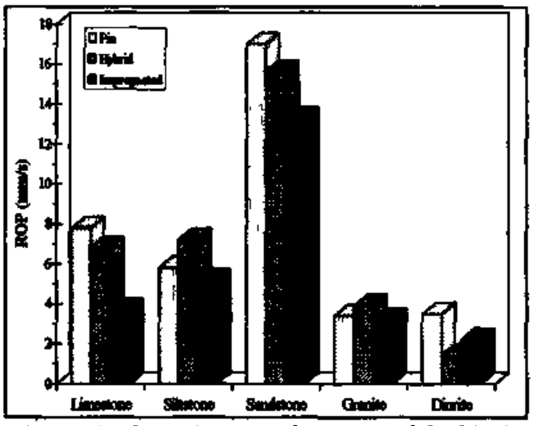

Figure 13 The optimum performances of the bits in rock types at 1650 rpm.