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An instrumented laboratory machine for the evaluation of drill-bit performance

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SYNOPSIS

A fully instrumented laboratory drilling machine is described. It is designed to produce realistic drilling conditions with diamond microbits of 20 mm diameter. A computer-controlled data-logging system records the net power consumption, rotational velocity, bit thrust, torque, and penetration rate. Tests can be conducted under conditions of set thrust and rate of advance.

In the tests reported, there is a significant correlation between the rock drillability and the measured rock properties of relative abrasion resistance and uniaxial compressive strength. Wear of a diamond bit is a crucial factor that cannot be determined simply from rock properties. Realistic drillability testing with appropriately scaled microbits is a convenient and economical way of evaluating diamond-bit performance and determining rock drillability.

SAMEVATTING

'n Volledig geïnstrumenteerde laboratoriumboormasjien word beskryf. Dit is ontwerp om realistiese boortoestande met diamantmikroboorpunte met 'n diameter van 20 mm te skep. 'n Rekenaarbeheerde dataregistreerstelsel registreer die netto kragverbruik, draaisnelheid, boordrukkrag, wringkrag en penetreertempo. Die toetse kan uitgevoer word onder vasgestelde toestande wat die drukkrag en vorderingstempo betref.

In die toetse waaroor verslag gedoen word, is daar 'n beduidende korrelasie tussen die rots se boorbaarheid en die gemete rotseienskappe te wete relatiewe skuurbestandheid en eenassige druksterkte. Die slytasie van 'n diamantboorpunt is 'n kritieke faktor wat nie bloot aan die hand van rotseienskappe bepaal kan word nie. Realistiese boorbaarheidstoetse met paslik geskeduleerde mikroboorpunte is 'n gerieflike en ekonomiese manier om die werkverrigting van boorpunte te evalueer en die boorbaarheid van rotse te bepaal.

Introduction

The variety of diamond bits available for rock drilling has increased considerably in the past few years with the introduction of new polycrystalline diamond (PCD) products[1]. Three types of core bits are now produced: natural-surface set bits, impregnated synthetic diamond bits, and bits set with synthetic polycrystalline diamond pads or geometric inserts. Each type includes a range of variations in face geometry, matrix composition, diamond (or PCD) size and shape, and optimal operating conditions.

Testing the performance of this wide range of bits in a correspondingly wide range of rock types is an essential part of the design and development of these products. Drilling tests in the field and in the laboratory are also indispensable for evaluating the performance of specific bit designs to facilitate the rational selection of appropriate bits for particular applications[2-4]. It is necessary to be able to conduct drilling tests in a wide variety of rock types because petrographic factors, such as free quartz content, grain size, and mineralogy, have a significant and sometimes crucial influence in the drilling resistance of rock[5-7].

The major advantage of laboratory testing of diamond-bit drilling is the ease with which the drilling parameters—set thrust or set rate of advance, rotational speed, flushing rate and pressure, and fluid composition—can be controlled and monitored. Field drilling rigs have rudimentary instrumentation generally unsuitable for the taking of useful measurements, and laboratory testing avoids transporting the drilling rig to test sites of different rock types. The reduced cost of smaller bits also makes it possible to run numerous tests at less expense. On the other hand, the rock material drilled in the laboratory is usually relatively free of fractures and realistic discontinuities, and the dynamics of the drill string such as deflection cannot be investigated since the holes are necessarily short. Because of these limitations, field tests cannot be dispensed with in the evaluation of long-term drilling performance, but valuable guidelines for field tests can be established economically in the laboratory.

This paper describes the construction and operation of an instrumented laboratory drilling machine suitable for use in the evaluation of the performance of microbit drills and in tests on the drilling resistance of rocks. The machine has been used specifically in studies of the drilling mechanisms and diamond wear in impregnated diamond-bit drilling[7-11]. The results of a series of drillability tests with such bits is discussed in this paper for illustrative purposes.

The Laboratory Machine

The core-drilling machine is based on a power-fed pillar drill (Fig. 1). It is capable of producing realistic drilling conditions using bits of 20 mm diameter to simulate the operation of full-scale laboratory machines[12,13]. The 1 kW machine has a maximum spindle speed of 3500 rev min^{-1} with a controlled vertical quill movement of 110 mm. A cast light-alloy wheel 460 mm in diameter was fitted to the manual feed lever so that tests could be con-

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ducted under conditions of set thrust. Several turns of wire rope round the wheel pass to a Teflon pulley attached to the concrete ceiling and a variable weight provide the load. To be able to conduct tests under a set rate of advance, the feed-rate gearbox was modified to provide a range of advance rates from 0,011 to 0,1 mm rev^{-1}.

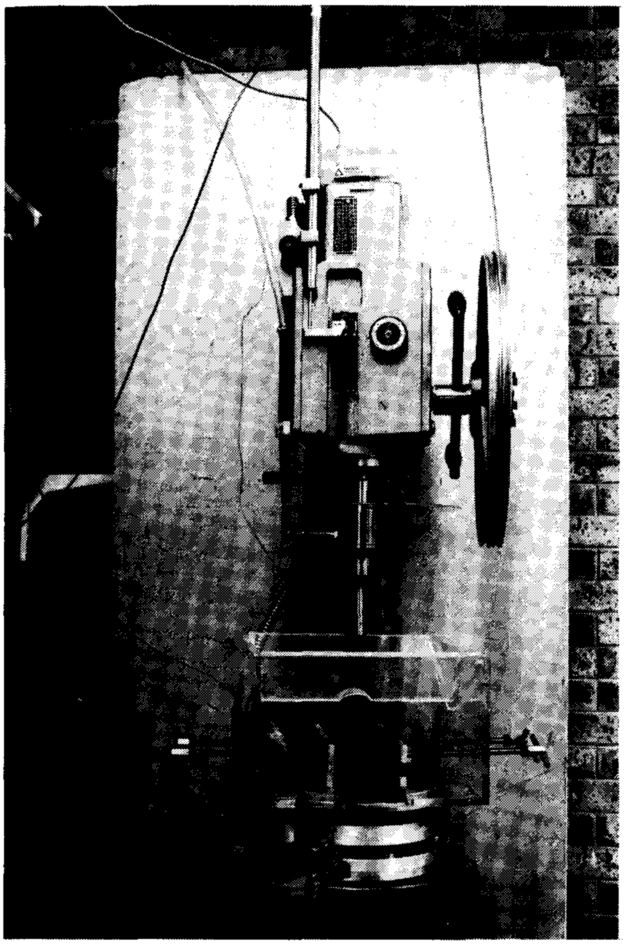

Fig. 1—The instrumented drilling machine

A 100 mm cube of the rock to be tested is clamped inside a Perspex splash box mounted on a three-tier aluminium turntable. A large thrust bearing between the upper two discs allows the splash box freedom to rotate. Linear bearings enable this assembly to move vertically relative to the bottom disc bolted to the turntable of the drilling machine (Fig. 2). All the bearings are lubricated frequently with water-repellant silicone aerosol. Mains water, with a flow of 300 to 400 litres per hour at about 200 kPa pressure, is used for flushing and cooling. The water flows through a flowmeter and pressure gauge, and then enters the drill string through a water-swivel assembly fitted with easily replaced seals.

Electronic Instrumentation

Five variables are measured continuously by a data-acquisition and control unit with a microcomputer to provide a detailed record of each test and the data from which the results are calculated. An electronic excitation interface board provides the power, and carries the instrument amplifiers for the wattmeter, rotation meter, thrust and torque load cells, and penetration meter.

The gross *power consumption* is measured by a recording wattmeter in the mains supply line. A standard calibrated wattmeter is used to calibrate the recording wattmeter, which is then corrected for load-dependent losses in the drilling machine by an established method[14]. The values obtained from this procedure are used in the calculation of the percentage efficiency at various levels of power consumption and in the plotting of a calibration curve (Fig. 3). The seals in the water swivel suffer significant degradation with operational life, which results in a diminishing loss of energy to friction; calibration has therefore to be carried out before each drilling test[7,10]. This is greatly facilitated by the use of the computer, which calculates a least-squares best-fit curve and calibration formula for the load-dependent power losses in each test.

The *rotational velocity* of the spindle is measured with an opto-isolator and a brass crown with two vertical blades mounted on top of the spindle. This system is calibrated with an adjustable xenon strobe.

The *bit thrust* is measured with a waterproof load cell set into the base disc of the specimen turntable. This allows a bit pressure of up to 30 MPa to be used with the 20 mm diameter bits.

The *torque* force generated in the specimen is measured by a load cell. A rigid steel beam clamped to the upper disc of the turntable impinges against the load cell to restrain the rotation of the splash-box assembly. This arrangement is preferable to a strain-gauged beam because of the wide range of torques experienced.

The position of the drill bit and the *penetration rate* is measured by a d.c. linear voltage differential transformer with a 150 mm linear range covering the full travel of the quill.

The Drilling Test

The drilling test starts with a computer-controlled routine to calibrate the wattmeter for the net power consumption and to record the test parameters. These are rock type, bit formulation, and set thrust or, alternatively, set rate of advance. The data-logger channels are sampled for zero readings, and the start of active drilling is detected by a sudden increase in power consumption. The five channels are then sampled once a second during the test, and the primary data are stored on disc for subsequent computation.

The final record for each test consists of a computer printout of the calculated drilling variables. These include the test duration, distance drilled, mean power output, mean bit pressure, mean bit torque, mean advance per revolution, and average specific energy calculated from the wattmeter and independently from the torquemeter. Computer-drawn plots of the relevant variables against drilling distance act as a visual record of the test (Fig. 4).

The bit wear is represented by mass loss and by linear bit wear, which is measured in a micrometer jig. The diamond wear, drilling detritus, and worn track broken out of the rock specimen are studied by optical and scanning electron microscopy. The rock drilled is characterized by optical petrography, the uniaxial compressive strength, and the relative abrasion resistance (R.A.R.), quartz being used as the standard[7,10].

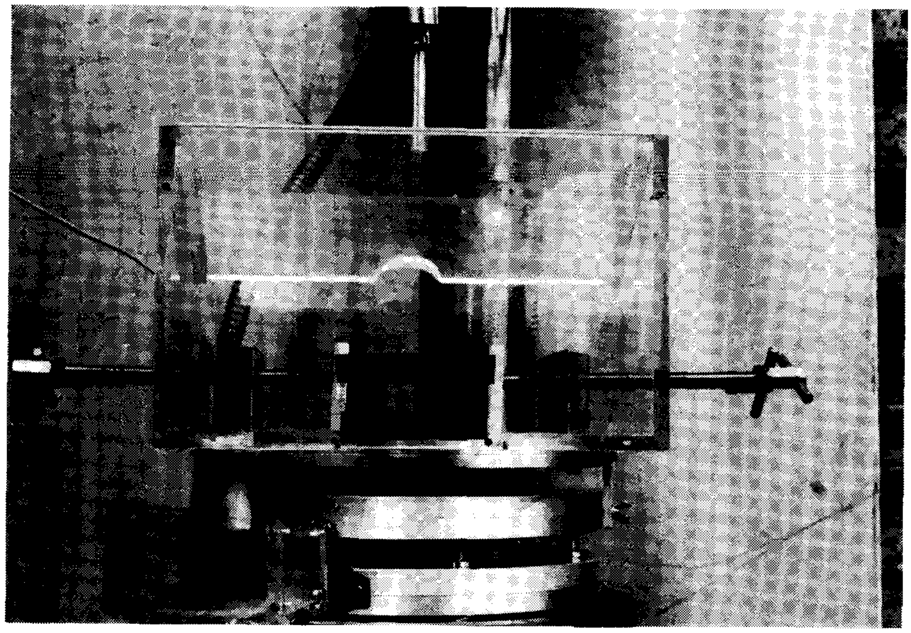

Fig. 2—The specimen clamp, splash box, and turntable assembly

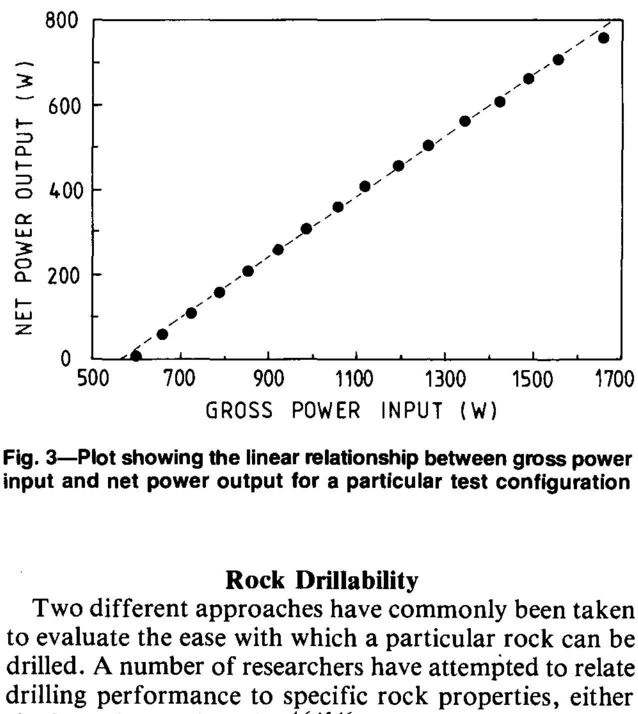

Fig. 3—Plot showing the linear relationship between gross power input and net power output for a particular test configuration

Rock Drillability

Two different approaches have commonly been taken to evaluate the ease with which a particular rock can be drilled. A number of researchers have attempted to relate drilling performance to specific rock properties, either singly or in combination[4,6,15,16]. Alternatively, attempts have been made to establish a drillability index based on the drilling performance of a standard microbit, usually a rotary tungsten carbide chisel bit[17-19].

There is lack of agreement on the choice of the performance variable most appropriate to describe the ease of drilling. Penetration rate has been related to a selection of rock properties including hardness, strength, and abrasiveness[4,6,20]. Specific energy has also been chosen as a variable to describe drillability[21,22]. As an additional factor, drillability evaluations based on microbit tests usually include an index of wear of a standard metal bit after the drilling of a set distance under set conditions[17,18]. Although a number of researchers have found uniaxial compressive strength to correlate strongly with drilling performance[4,20,23], there is no generally accepted method for the determination of rock drillability either from the measurement of rock properties or by experimental evaluation.

The Drillability Tests

In the drillability tests presented here, ten different materials were drilled under a set rate of advance of 0,044 mm rev^{-1} at 3500 rev min^{-1}. Impregnated diamond microbits of a standardized formulation were used—De Beers SDA 100 synthetic grit at concentration 30 in a bronze matrix with inner and outer diameters of 12 mm and 20 mm respectively. The relative abrasion resistance and uniaxial compressive strength of the materials drilled are given in Table I.

TABLE I
RELATIVE ABRASION RESISTANCE AND UNIAXIAL COMPRESSIVE STRENGTHS OF THE MATERIALS DRILLED

Material	Relative abrasion resistance	Compressive strength (n = 4) MPa
Single-crystal quartz	1 ± 0,001	360 ± 120
Jaspilite	0,809 ± 0,002	489 ± 132
Granite	0,569 ± 0,003	186 ± 48
Dark norite	0,470 ± 0,002	287 ± 35
Light norite	0,440 ± 0,002	209 ± 28
Quartzite	0,436 ± 0,004	250 ± 87
Syenite	0,400 ± 0,006	176 ± 27
Single-crystal felspar	0,395 ± 0,003	219 ± 103
Sandstone	c 0,04	41 ± 6
Marble	c 0,03	138 ± 36

The Results

The reactive load, expressed as bit pressure, and the specific energy of drilling calculated from the torquemeter output were used as measures of drilling performance. The significance of the relationships between the performance variable and the rock properties was tested by simple

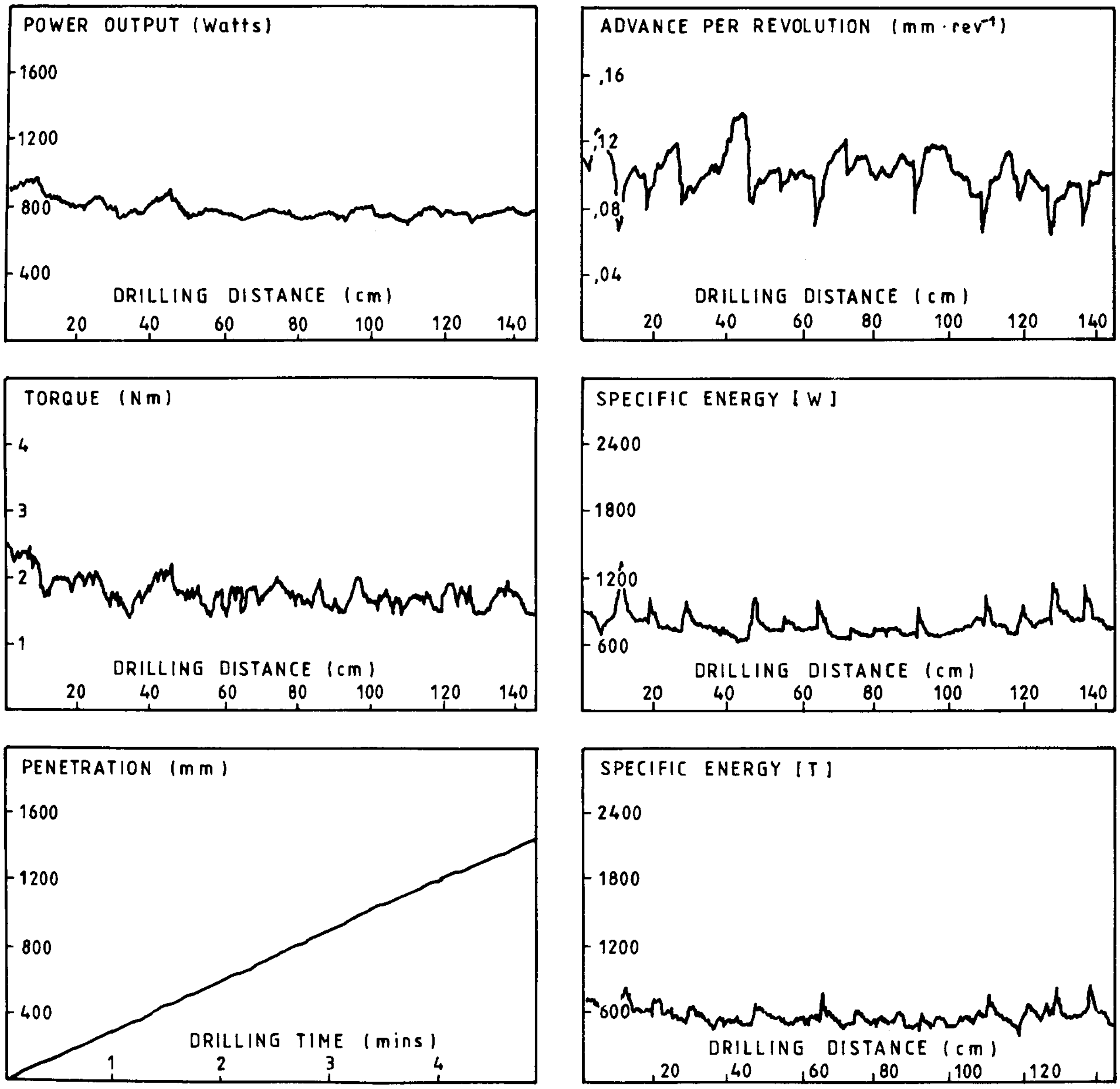

Fig. 4—Computer plots of the drilling variables for a single test

linear regression.

The specific energy was best predicted by the product of relative abrasion resistance and uniaxial compressive strength, with a correlation coefficient of r = 0,94 (Fig. 5). This correlation is good in view of the scatter to be expected in the results because of the inherent rock variability. The mean bit pressure was best predicted by the relative abrasion resistance, with a correlation coefficient of r = 0,90 (Fig. 6).

Discussion

Uniaxial compressive strength in rocks depends directly on tensile strength and shear strength[23], and the relative abrasion resistance is affected directly by the mineralogical composition and the rock fabric or structure[7]. Together, the two measured properties represent a variety of relevant rock properties and, because they are easily determined, they form a simple index of drillability.

However, any standardized test of rock drillability must take bit wear into consideration[4]. The relative abrasion resistance and uniaxial compressive strength do not predict the diamond wear or the bit wear, which is affected very significantly by rock type. For instance, at high bit pressure, the wear of the bits drilling sandstone was extreme. Such low-strength, abrasive rocks with easily excavated grains of hard minerals like quartz are readily drilled, but at the cost of high rates of bit wear. The lack of correlation between relative abrasion resistance and bit wear in these tests indicates that the bit wear in impregnated diamond-bit drilling does not proceed by direct abrasion. The shape, size, and hardness of the particles generated by the drilling all affect the rate of wear on the bit matrix by a predominantly erosive mechanism. The mechanisms of diamond wear and bit wear in impregnated diamond drilling have been described in detail elsewhere[7–11].

Previous attempts at predicting drilling performance in terms of measured rock properties have not been very successful. Drillability tests involving the calculation of an abrasive index[18] or the measurement of both penetra-

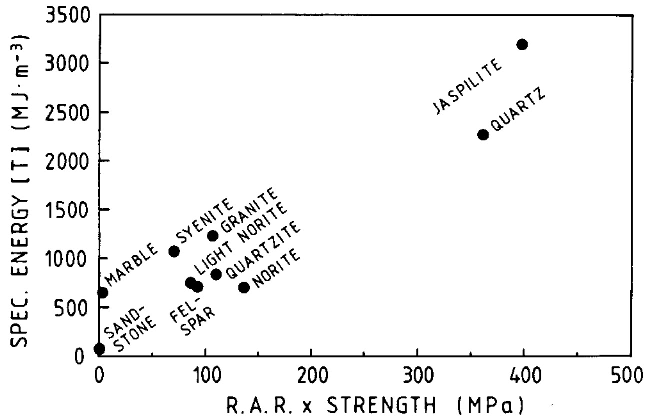

Fig. 5—Plot showing the relationship between specific energy and the product of relative abrasion resistance (R.A.R.) and uniaxial compressive strength for tests at a set rate of advance of 0,044 mm rev^{-1}

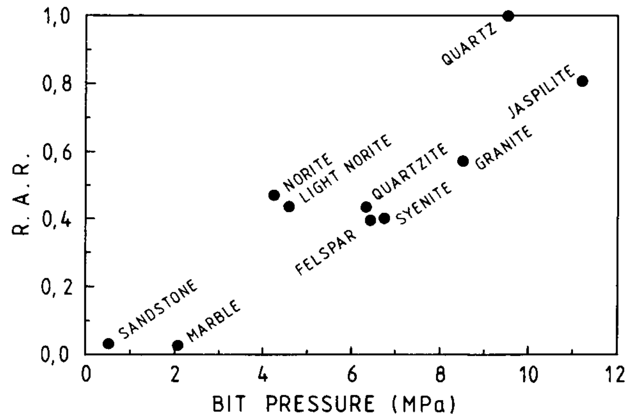

Fig. 6—Plot showing the relationship between relative abrasion resistance (R.A.R.) and reactive bit pressure for tests at a set rate of advance of 0,044 mm rev^{-1}

tion rate and bit wear with a standard bit[19] are more successful because they allow for the petrographic characteristics of the rock, as well as the effects of bit wear. However, neither method considers the effect of appropriate bit formulation or geometry in the drilling of different rock types.

Any standardized test will vary in its appropriateness for a variety of rock types, and in extreme cases a standardized bit, especially if it is a tungsten carbide bit[19], may not be able to drill a given rock at all. It is clear that, with different diamond-bit formulations, the relationship between the diamond size and the grain size of some rocks can have a highly significant effect on performance[7]. For instance, in the drilling of coarse-grained rocks with impregnated diamond bits, the relatively small diamonds traverse single grains, causing predominantly intragranular fracture. If the diamond size approaches or exceeds the grain size of the rock, entire grains can be excavated by intergranular fracture, particularly in weakly cemented sandstones. This increases the penetration rate but also increases the bit wear dramatically. Realistic drillability testing in the laboratory requires a range of diamond bits to accommodate the extreme variations in rock properties and corresponding drilling responses.

Conclusions

(1) An appropriately instrumented and adaptable laboratory machine can be used in the study of the mechanisms of diamond drilling, and provides meaningful measurements of drill-bit performance. In this way, rock drillability can be evaluated realistically, allowing for the dynamic effects of bit wear and diamond wear.

(2) For hard, medium-grained rocks drilled with impregnated diamond bits of appropriate formulation, there is a linear relationship between the drilling performance in terms of specific energy and the readily measurable physical rock properties of relative abrasion resistance and uniaxial compressive strength. This is a simple index of rock drillability.

(3) The diamond wear and the bit wear that play a crucial role in diamond-bit drilling cannot be predicted in this way because petrographic factors such as grain size and shape, and mineralogy, can crucially affect the bit wear and the drilling performance. This shortcoming is shared by other methods used in the evaluation of rock drillability[17-19].

(4) In such evaluations, there is no effective alternative to drilling the rock in question with a drill bit similar to that which will be used in the field, and under realistic operating conditions. Laboratory testing with scaled diamond microbits is an economic complement to full-scale testing in the field.

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Analytical chemistry

The Third International Symposium on Analytical Chemistry in the Exploration, Mining, and Processing of Materials will be held in Sandton (near Johannesburg) from 2nd to 7th August, 1992. The Symposium is being held under the aegis of The International Union of Pure and Applied Chemistry (IUPAC).

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