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An experimental investigation into the drilling and physico-mechanical properties of a rock-like brittle material

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ABSTRACT

Energy efficiency (specific energy) and penetration rate in rock drilling processes are dependent on various operational variables (applied load, torque etc.) in addition to the physico-mechanical properties of the rock being drilled. Experimental work, using a laboratory drilling setup, was carried out to investigate the interplay between the various operational variables and the physico-mechanical properties of cement mortar, an analogue for natural rock. Unconfined Compressive Strength (UCS) tests were first performed to characterise the cement mortar. The penetration rate and specific energy were determined for various experimental drilling scenarios and correlated with the operational variables employed for these drilling scenarios and the physico-mechanical properties of the cement mortar used. The results of the experimental work demonstrate the significance of applied load and torque for both penetration rate and specific energy in drilling. Additionally, the experimental results emphasise the influence of material (rock or cement) properties on the penetration rate and specific energy in drilling. From the testing data, empirical relationships are proposed for the purpose of determination of both penetration rate and specific energy for certain operational variables, and for given UCS of the material to be drilled.

1. Introduction

In the past several decades, due to the importance of rock drilling in mining and petroleum engineering applications, a number of studies have addressed the drilling properties of brittle materials such as rock and mortar. The drillability of rock mainly depends on operational variables (controllable parameters), and rock material and joint properties (uncontrollable parameters). Some of the operational variables can include rotational velocity, applied load and flushing rate. The objective for those concerned with planning a drilling project is to understand how these variables govern penetration rate and energy expenditure in the drilling process.

Many researchers have investigated (theoretically or experimentally) the drillability of materials by correlating the penetration rate (and other controllable parameters) with the various rock properties, to produce a variety of empirical relationships to predict drilling rate and energy requirements in drilling. Teale (1965) proposed the concept of specific energy as a simple means of assessing rock drillability. Specific energy is defined as the energy required to excavate a unit volume of rock in the drilling process. It is used as a means of evaluating efficiency in the drilling process. There are many ways to measure specific energy for the drilling process, but the most common approach uses Eq. (1).

$$SE_m = \left[\left(\frac{1}{1000}\right)\left(\frac{2\pi NT}{\left(\frac{\pi}{4}\right)d^2 PR}\right)\right] \quad (1)$$

where SE_m is the measured specific energy, N is the rotation speed, T is the torque, d is the borehole diameter and PR is the penetration rate.

Penetration rate is the most important of the operational variables in the drilling process (Sievers, 1950; Hartman, 1959; Selmer-Olsen and Lien, 1960; Protodyakonov, 1962; Gnirk, 1963; Teale, 1965; Selim and Bruce, 1970; Selmer-Olsen and Blindheim, 1970; Hustrulid and Fairhust, 1971; Mellor, 1972; Tandanand and Unger, 1975; Pathinkar and Misra, 1976; Rabia and Brook, 1980; Rabia, 1982, 1985; Howarth et al., 1986; Farmer and Garritly, 1987; Fowell, 1993; Krupa et al., 1993; Thuro, 1997; Huang et al., 1998; Schunnesson, 1998; Kahraman et al., 2000; Brook, 2002 and Kahraman et al., 2003). Selim and Bruce (1970), using stepwise linear regression analysis, developed a penetration rate model that is a function of the drill power and the physical properties of the rock being drilled.

The theoretical specific energy, as defined by different research workers, has proved to correlate well with penetration rate. Sinkala

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(1991) derived the following theoretical expression for the minimum torque necessary to maintain constant bit rotation (Eq. (2)), and found a good agreement between practical and theoretical values.

$$\tau = \left(\frac{FD}{3}\sqrt{\frac{R}{15f\theta}}\right) \quad (2)$$

where τ is the bit torque, F is the thrust on the bit, D is the bit diameter, R is the penetration rate, f is the piston impact frequency, and θ is the button diameter.

Fowell (1993) pointed out that specific energy in rock cutting is affected significantly by tool geometry, cutter spacing, tool penetration and rock properties. These factors will of course influence formulas used to describe specific energy with respect to the operational variables. However, the properties of the drilled medium will also influence the specific energy in the drilling process. Hughes (1972) and Mellor (1972) provided a simplified formula to calculate specific energy (SE_c) from the compressive strength (σ_c) and Young's modulus (E) of the drilled medium:

$$SE_c = \sigma_c^2 / _{2E} \quad (3)$$

A good understanding of the role of the various operational and material parameters and how they govern the drillability of brittle materials is important for cost and resource assessment in large rock drilling projects. However, limited data exists in this area and a significant amount of work remains to be performed on the topic of the drillability of brittle materials.

This paper reports on an experimental study carried out to explore the interplay between various operational parameters and the physico-mechanical characteristics of the brittle material being drilled. The investigation reported here employs an experimental drilling setup that is used to perform drilling tests on cement mortar. Cement mortar is used as an analogue for rock due to the reproducibility it offers in terms of the material characteristics of the samples used for testing.

2. Materials used in the experimental work

2.1. Cement

General Purpose Cement (GPC) is defined in AS 3972 (1997) as ‘hydraulic cement which is manufactured as a homogeneous product by grinding together Portland cement clinker and calcium sulphate, and which at the discretion of the cement manufacturer may contain up to 5% of mineral additions for use in general purpose concrete applications, cement-based products, mortars and grouts’. Portland cement consists of carefully proportioned mixtures of calcium carbonate, alumina, silica, and iron oxide which, when calcined and sintered at high temperatures, give a new group of chemical compounds capable of reacting with water to form cementitious compounds. Portland cement includes four major minerals, being: tricalcium silicate (C_3S), dicalcium silicate (C_2S), tricalcium aluminate (C_3A), and tetracalcium aluminoferrite (C_4AF). The specific gravity of the cement used for the testing was 3150 kg/m^3. Initial and final setting times of the cement were 4 and 5 h, respectively, and the Blaine specific surface area was 3140 cm^2/g. The chemical composition of the GPC used in production of the cement mortar for the testing is given in Table 1.

Table 1
Chemical composition of GPC and sand.

Oxide	Cement (wt.%)	Sand (wt.%)
Silica (SiO_2)	20.60	81.40
Alumina (Al_2O_3)	5.60	4.47
Iron oxide (Fe_2O_3)	4.20	1.40
Lime (CaO)	61.90	0.82
Magnesia (MgO)	2.60	1.48
Gypsum ($CaSO_4 \cdot 2H_2O$)	2.79	1.35
Alkali (K_2O)	0.83	n/a
Alkali (Na_2O)	0.14	n/a
Titania (TiO_2)	0.13	1.81
Phosphorus (P_2O_5)	0.11	0.01
LOI	1.09	7.26

Table 2
Sand particle size distribution, as determined from sieve analysis.

Sieve size (mm)	Proportion (wt.%)
5–9.75	2.66
2.36–5	3.71
1.18–2.36	16.43
0.6–1.18	17.6
0.3–0.6	17.03
0.15–0.3	34.87
0–0.15	7.67

2.2. Sand

Sand was used in the production of the cement mortar. The dry unit weight of the sand, measured according to the International Society for Rock Mechanics (ISRM, 1981), was 2410 kg/m^3. The density of the pore-free pulverised sand was 2650 kg/m^3. Sand aggregates were sieved using standard sieves and separated into seven grain-size groupings of 0–0.15 mm, 0.15–0.3 mm, 0.3–0.6 mm, 0.6–1.18 mm, 1.18–2.36 mm, 2.36–5 mm and 5–9.75 mm. A mixture displaying the particle size distribution given in Table 2 was made from these seven grain-size groupings. The chemical composition of the sand used in production of the cement mortar for the testing is given in Table 1.

3. Cement mortar preparation and composition

Mixture proportions of 1:5, by weight, of GPC and sand, respectively, were used to produce the cement mortar. These cement mortar mixture proportions resulted in an approximate quantity of GPC of 325 kg for each unit volume (m^3) of cement mortar produced. The water–cement ratio for mixing was kept constant at 0.65. Table 3 shows the composition of the cement mortar mixtures produced for the experimental work.

Fresh and air-dry unit weights of the cement mortar, measured in accordance with ASTM C138 (2002) and ASTM C567 (2002), were calculated at 2550 ± 29 and 2400 ± 23 kg/m^3, respectively. Slump values measured according to ASTM C143 (2002) were 6 ± 1.5 cm for the mixture.

Standard cylindrical specimens 100 mm in diameter and 200 mm in length were prepared from fresh cement mortar mixtures. Complete compaction of the samples was performed by means of

Table 3
Approximate mixture composition (by weight) per cubic metre of cement mortar.

		Sand (kg) by grain-size grouping (mm)						
c (kg)	w (kg)	9.75–5	5–2.36	2.36–1.18	1.18–0.6	0.6–0.3	0.3–0.15	0.15–0
325	225	44.38	60.42	267.80	286.83	277.54	568.35	125.02