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Temperature Effects on Rock Properties: A Controlled Laboratory Investigation for Drilling Applications

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Abstract: Friction between the rock and bit during drilling generates heat, causing thermal stress and rock failure. About 80% of the bit's energy is released as heat, 1.5–10% causes residual bit changes, and 8–10% is used for rock destruction. Temperature variation was analyzed at different depths with the drill bit at 6 mm. Interface temperatures were 56°C, 49°C, 45°C, 43.5°C, and 40°C for all 5 types of rock samples considered. Temperatures at 14 mm, 22 mm, and 30 mm were also recorded, stabilizing at 23°C for all rock types at 30 mm. The highest temperature at 6 mm gradually decreased to 30 mm, indicating low heat transfer in rocks. FGS (grey), FGS (pink), and shale, with SiO_2 contents of 16.45%, 30.22%, and 25.54% (wt.%), had coefficient of wear rate of 0.2121, 0.2742, and 0.1871 mg/Nm and bit-rock interface temperatures of 84°C, 147°C, and 89°C were achieved.

Keywords: Rotary drilling, rock properties, interface temperature,

I. INTRODUCTION

There are three main drilling methods used in the mining industry. Of these, rotary drilling is the most common drilling method applied in large open-pit mines. Heat generated during the drilling process increases the temperature of the drill bit and rock. The temperature increase depends on the operating parameters and drilling time. The proper selection of a drill bit for the existing geological structure is very important for economical drilling. Several types of bits exist, and the correct selection increases the penetration rates while reducing wear and tear. The workpieces were instrumented using the embedded thermocouple method, which has a response time of 10 microseconds [1]. Because of the high thermal inertia of the welded thermocouples, the thin insulated wire junction is embedded in the workpiece for more accurate measurement of transient temperature [2, 3].

Temperature during drilling was measured using the embedded thermocouple method at different workpiece locations. Hollow drill bits generate lower temperatures than conventional ones [4]. Since experimental and analytical studies are time-consuming, ANN techniques effectively model and predict results [5]. A 1D transient thermal conductivity model accurately predicted drilling temperature for lunar regolith [6]. Thermocouples and platinum resistors were embedded in the drill tool and regolith simulant for temperature measurement [7]. Micro-bit drilling tests on sandstone showed coupled effects of pressure and temperature were more significant [8]. A predictive model studied the geothermal radius influence, showing <10% error between recorded and modeled temperatures, confirming its accuracy [9]. Additionally, larger hole and probe diameters reduced thermal conductivity, delaying heat transfer.

Temperature and operational factors reduce drill bit life during drilling in soft and hard rocks [10]. To produce thermal fatigue, which increases wear at the cutter head [11]. Damage to the microstructure of the bit leads to a surface in an non-uniform, because of the roughness and heterogeneity of rock [12]. The coefficient by Archard effectively estimates the abrasiveness of the tool (Sarkar et al., 2013). Under different cooling, and bit balling, thermal stress can lead to plastic deformation of the cutter [13]. The PDC bit wear curve follows four phases: entry break, diamond layer wear, carbide substrate wear, and rapid breakdown [14]. Thermally stable PDC cutters minimize thermal stress, while drilling temperature measurements monitor bottom-hole conditions [15-16]

II. EXPERIMENTAL INVESTIGATIONS

An NX core rock sample with a 54mm diameter and 135mm length was used according to ISRM standards. Tests were conducted in a CNC machine for different operational parameters were considered [22], and different rock properties. The temperature is the measured output response for a tungsten carbide masonry drill bit under rotary drilling and is represented in Fig.1.

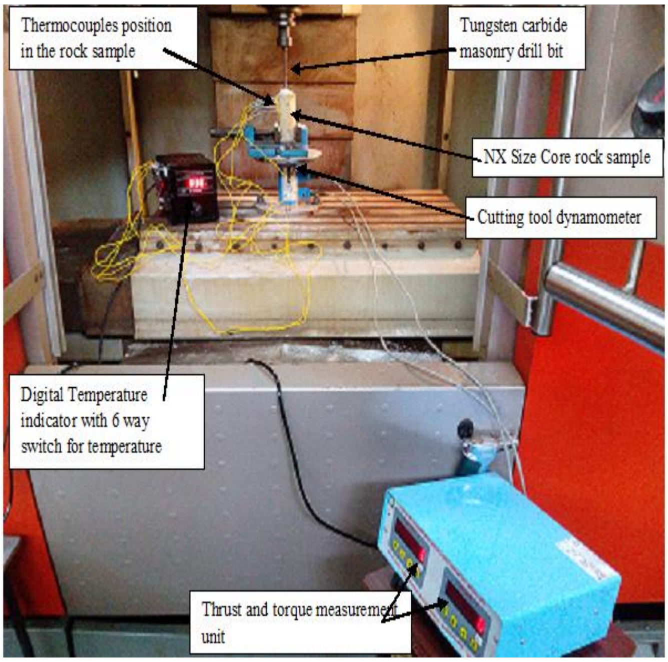


Fig. 1 A detailed setup for measuring rotary drilling temperature at the bit-rock interaction.

III. ROCK SAMPLES AND ITS PHYSICO-MECHANICAL PROPERTIES

Fig. 2 were prepared to evaluate UCS, BTS, density, and Los Angeles abrasion, following ISRM-recommended methods.


(a) (b)

(c)


(d) (e)

Fig. 2 Core samples of (a) FGSP (b) FGSG (c) Limestone (d) MGS (e) Shale

IV. MEASUREMENT OF DRILL BIT WEAR RATE

Wear is the process to removal material at mating surface. It compromises the reliability and durability of nearly all machines by affecting their mating components. Consequently, effective wear control has become essential for developing advanced and dependable technologies in the future.

Each drill bit test included multiple drilling trials, with wear measured at intervals across the crown. The mass loss method, using a 0.1 g resolution electronic balance (Fig. 3), was the primary measurement technique. Mass loss reflected material removal from both the bit body and crown, with most wear occurring in the cutter and matrix, which directly contact the rock [17].

Fig. 3 Weighing balance

Equations are given below.

$$Wear\ rate\ coefficient\ \frac{wear\ rate\ (\frac{mg}{sec})}{SN\ (Nm/sec)}\ mg/Nm \quad (1)$$

$$Wear\ rate = \frac{Initial\ weight - final\ weight}{Drilling\ time}\ mg/sec \quad (2)$$

The Archard equation is a simple wear model based on asperity (surface unevenness) contact theory. It is expressed as W/LC = k, where W is the wear rate (mm³), L is the Length of slide (m), and C is the Load at normal condition (N).

$$Wear\ rate\ coefficient\ \frac{wear\ rate\ (\frac{mg}{sec})}{SN\ (Nm/sec)}\ mg/Nm \quad (3)$$

V. RESULTS AND ANALYSIS

Temperature variation was analyzed for different rock samples at various thermocouple depths when the drill bit reached 6 mm [20]. It can be seen from Fig. 4 that the temperatures at the bit-rock interface were 56°C for the FGS (pink), 49°C for the limestone, 45°C for the FGS (grey), 43.5°C for the shale, and 40°C for the medium-grained sandstone, respectively. Temperature readings were also recorded at 14 mm, 22 mm, and 30 mm depth, where it had stabilized at 23°C for all rock types. The highest interface temperature occurs at 6 mm depth and gradually decreases up to 30 mm, suggesting a lower heat transfer rate in rocks. Thus, a 30 mm depth was chosen as the standard for all rock sample experiments.

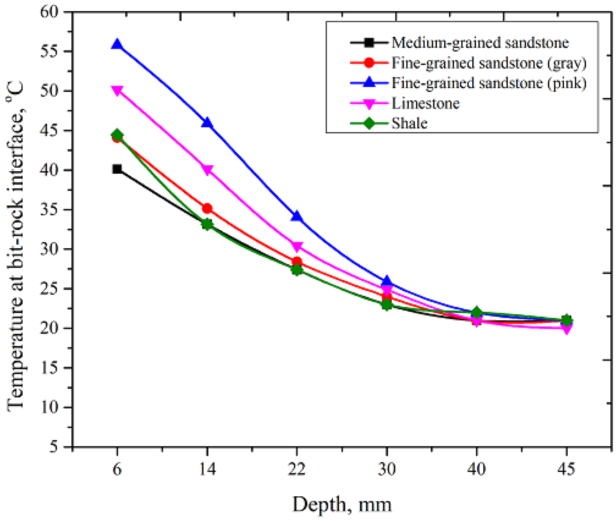


Fig. 4 Variation of temperature in the rock samples.

VI. INTERFACE TEMPERATURE BASED ON ROCK PROPERTIES

Table 1 provides the variation in rock properties with respect to temperature at the bit-rock interface during drilling. Figs. 5–8 give a clear indication that with an increase in the interface temperature, the values of UCS, BTS, and density increase. This is particularly because of the mineral constituents of the rock, specifically having high Moh's hardness values.

Table 1 Properties of rock and interface temperature for all five rock types.

Types of rock	UCS (Mpa)	BTS (MPa)	Density (gm/cc)	Los Angeles Abrasion (%)	Temperature in Average (°C)
MG	12.92	1.498	1.58	30.01	62.21
Limestone	15.61	1.981	2.01	27.96	69.28
FG	18.11	2.219	2.33	34.01	65.52
Shale	23.01	3.091	1.98	37.92	69.44
FGP	50.96	6.590	2.31	39.99	106.11

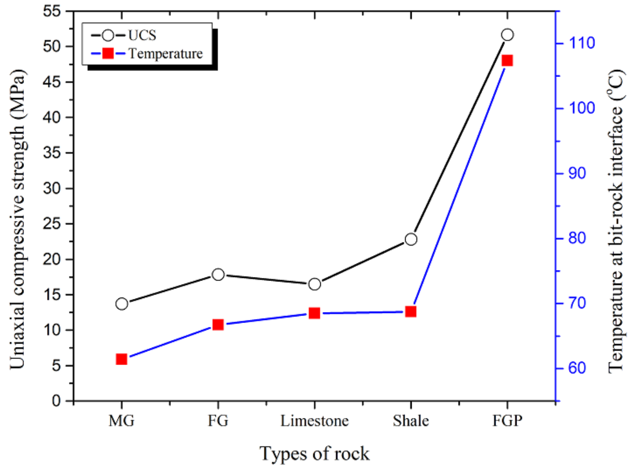


Fig. 5 Effect of temperature on UCS.

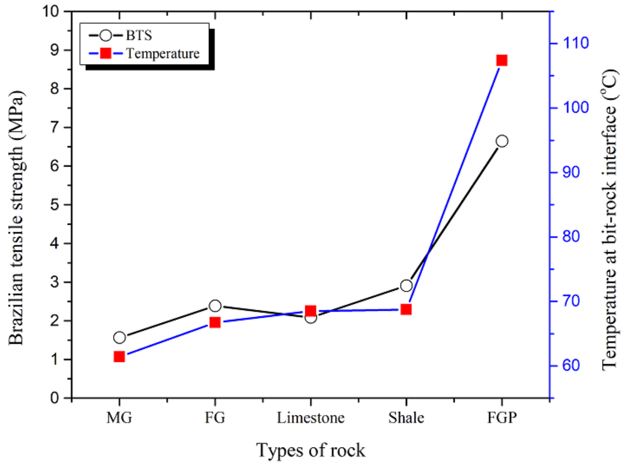


Fig. 6 Effect of at temperature on BTS

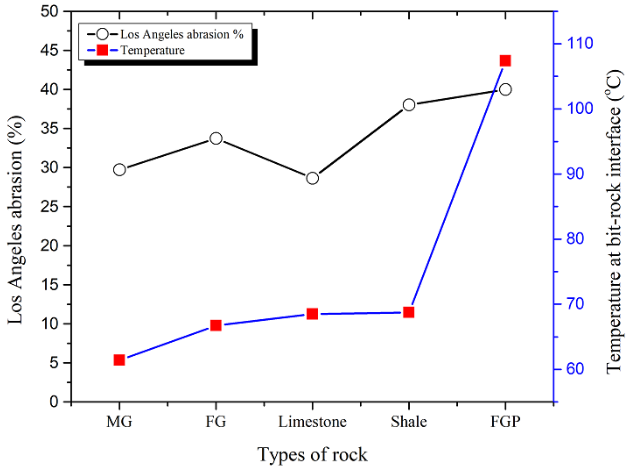


Fig. 7 Effect of temperature on Los Angeles abrasion loss

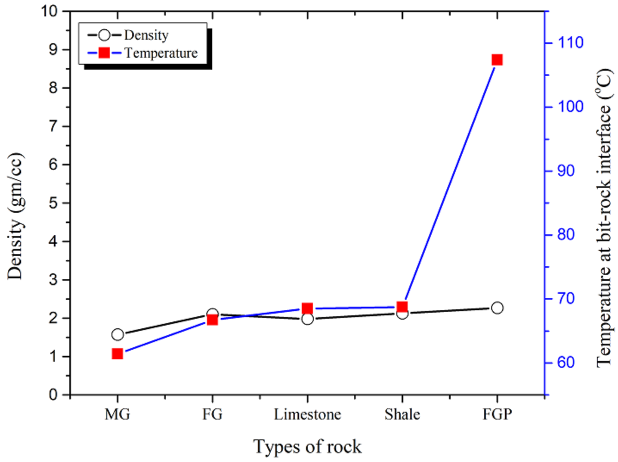
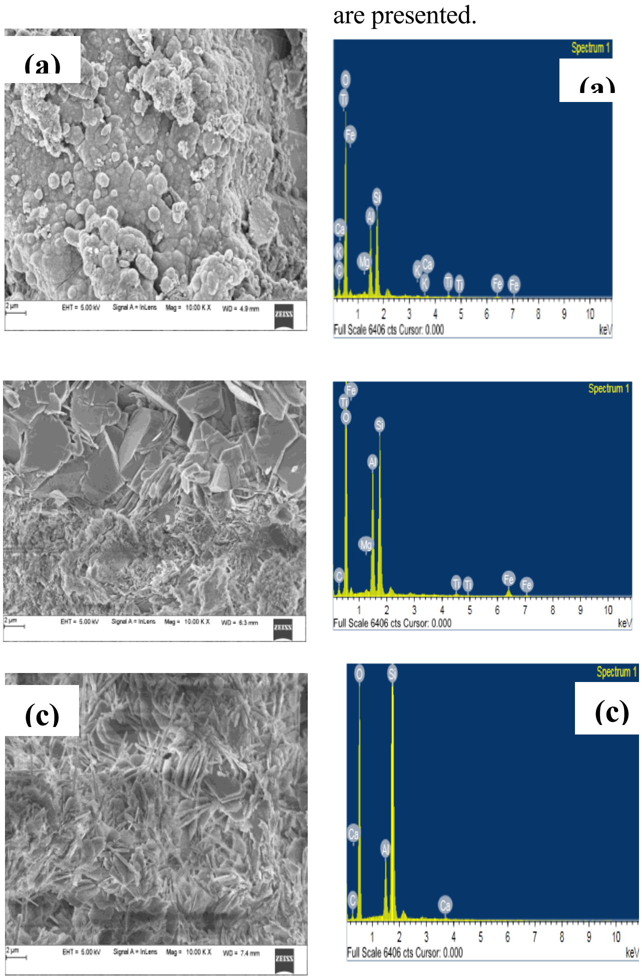


Fig. 8 Effect of interface temperature on density

A. Wear Test Results

4.3.1 EDS and SEM analysis

FESEM analysis for five rock types, namely MGS, FGS grey and limestone, shale, pink, is presented in Fig. 9(a)-(e). Besides that, EDS analysis has also been carried out to identify the content of silica in the samples. The results are presented.



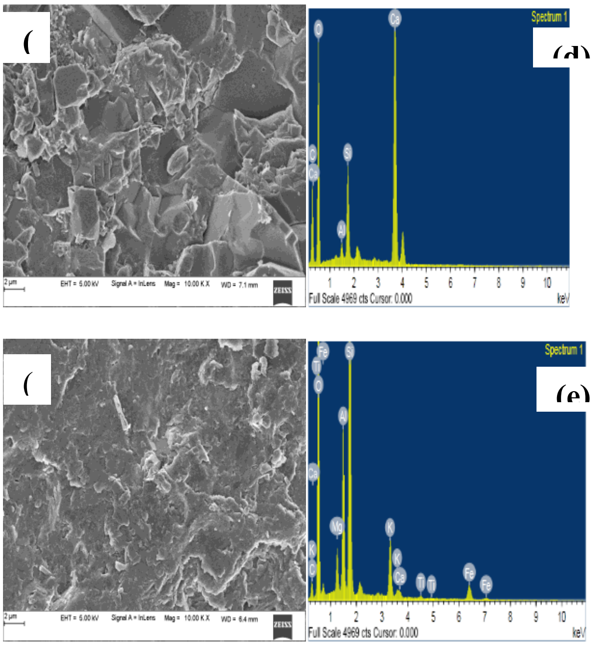


Fig. 9 SEM micrographs and EDS analysis for all 5 types of samples

4.3.2 Wear and bit interaction by considering UCS and SiO2

This experiment examined the correlation between uniaxial compressive strength (UCS), SiO_2 content, and tungsten carbide drill bit wear rate. Rock strength depends on the Moh's hardness of its minerals, where values above 5.5 indicate high abrasive wear [18]. SiO_2, with a Moh's hardness of 7, increases rock strength. EDS analysis identified varying silica content in five rock types, with UCS values presented in Table 1. Increased SiO_2 content [21] enhances rock hardness, affecting friction at the bit-rock interface, as illustrated in Fig. 10.

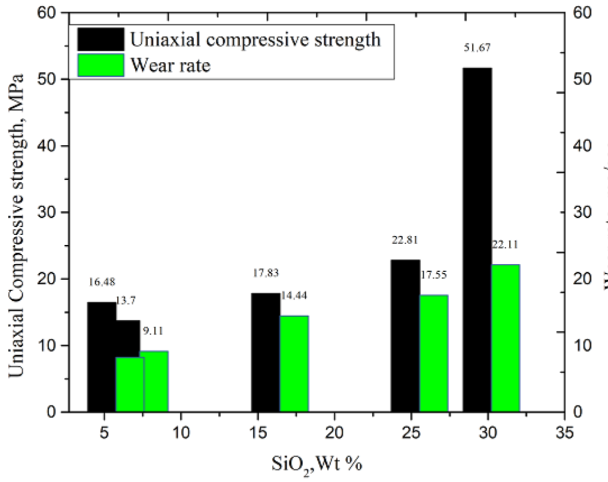


Fig. 10 wear rate and UCS correlation with SiO_2 vs. of the rock samples

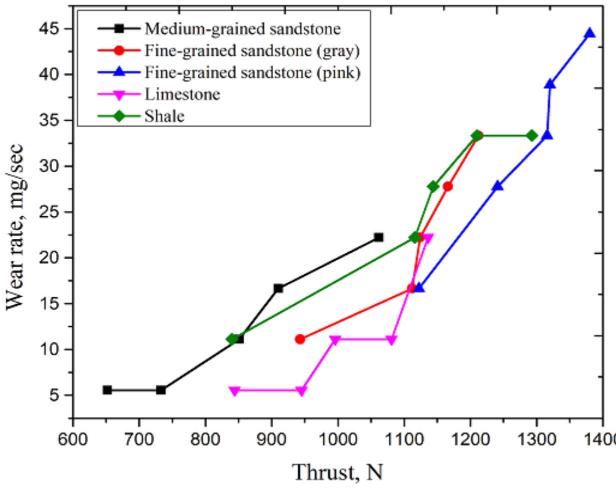


Fig. 11 Interaction between wear and trust for different rock samples

Fig. 11 illustrates the thrust effect on drill bit wear rate. Penetration rates of 2, 4, 6, 8, and 10 mm/min were tested, while diameter of the bit (16 mm) and spindle speed (450 rpm) remained constant. Results show that thrust increases with wear rate due to rock resistance and the higher force needed for drilling [19]. Fig. 12 gives the impact of temperature on drill bit wear rate. Silica content and corresponding temperatures were recorded as follows: medium-grained sandstone (7.30 wt.% at 91°C), FGSG (16.45 wt.% at 128°C), FGSP (30.22 wt.% at 236°C), limestone (5.17 wt.% at 120°C), and shale (25.54 wt.% at 147°C).With a Moh's hardness of 7, silica creates a ploughing effect, increasing mechanical force on asperities and raising the friction coefficient [19]. As silica content increases, heat transfer at the bit-rock interface also rises [13].

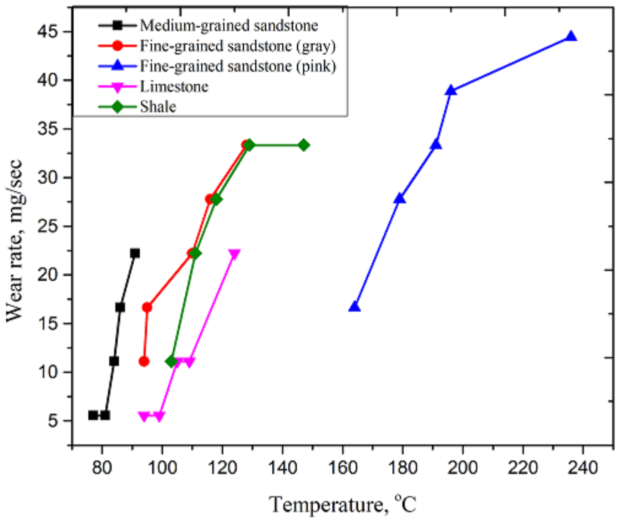


Fig. 12 Impact of temperature on drill bit wear rate.

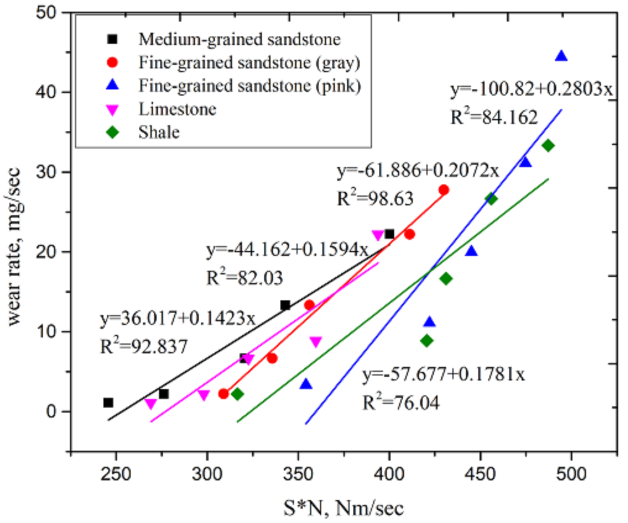


Fig. 13 Function of Spindle speed and load on wear rate

CONCLUSIONS

The present investigations were conducted in the laboratory scale with 5 different rock types. Temperature variation was analyzed at different depths with the drill bit at 6 mm, showing bit-rock interface temperatures of 56°C, 49°C, 45°C, 43.5°C, and 40°C for the five rock types. Temperatures at different depth stabilized at 23°C. The highest temperature at 6 mm gradually decreased to 30 mm, indicating low heat transfer. FGSG, FGSP, and shale, with SiO_2 contents of 16.45%, 30.22%, and 25.54%, had wear rate coefficients of 0.2121, 0.2742, and 0.1871 mg/Nm and bit-rock interface temperatures of 84°C, 147°C, and 89°C, respectively.

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