RESEARCH ARTICLE

Measurement of bit-rock interface temperature and wear rate of the tungsten carbide drill bit during rotary drilling

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Abstract: Rock drilling is an essential operation in mining industries. Temperature at the bit-rock interface plays a major role in the wear rate of the drill bit. This paper primarily focuses on the wear rate of tungsten carbide (WC) drill bit and the interrelationship between temperature and wear rate during rotary drilling operations conducted using a computer numerical control (CNC) machine. The interrelationship between the temperature and wear rate was studied with regard to three types of rock samples, i.e., fine-grained sandstone (FG) of uniaxial compressive strength (UCS) that is 17.83 MPa, medium-grained sandstone (MG) of UCS that is 13.70 MPa, and fine-grained sandstone pink (FGP) of UCS that is 51.67 MPa. Wear rate of the drill bit has been measured using controlled parameters, i.e., drill bit diameter (6, 8, 10, 12, and 16 mm), spindle speed (250, 300, 350, 400, and 450 rpm), and penetration rate (2, 4, 6, 8, and 10 mm/min), respectively. Further, a fully instrumented laboratory drilling set-up was utilized. The weight of each bit was measured after the bit reached 30 mm depth in each type of the rock sample. Furthermore, effects of the bit-rock interface temperature and operational parameters on wear rate of the drill bits were examined. The results show that the wear rate of drill bits increased with an increase in temperature for all the bit-rock combinations considered. This is due to the silica content of the rock sample, which leads to an increase in the frictional heat between the bit-rock interfaces. However, in case of medium-grained sandstone, the weight percentage (wt%) of SiO_2 is around 7.23 wt%, which presents a very low wear rate coefficient of 6.33×10^{-2} mg/(N·m). Moreover, the temperature rise during drilling is also minimum, i.e., around 74 °C, in comparison to that of fine-grained sandstone and fine-grained sandstone pink. In addition, this paper develops the relationship between temperature and wear rate characteristics by employing simple linear regression analysis.

Keywords: temperature; wear rate; drilling; simple linear regression

1 Introduction

Drilling of soft and hard rock formations, their drill bit life may be substantially reduced. This is due to the combined effect of temperature produced during drilling and the operational parameters considered [1]. Frictional heat and cooling cause thermal fatigue, which leads to higher formation of a wear flat at the cutter head [2]. Damage of the bit's microstructure shows the non-uniform surface, owing to the roughness of the rock sample as well as the heterogeneities

prevalent [3]. The temperature data acquired during drilling demonstrate the functionality of the tool embedded with microthermal sensors that generate rapid response and are more reliable in nature for both fundamental and in-process study [4]. To observe the abrasive characteristics of a tool, Archard's coefficient yields a better result [5]. Thermal stress depicts that plastic deformation of the cutter structure can occur under certain downhole conditions, such as thermal conductivity, rock properties, texture, cooling, bit balling, and transient phases [6]. Wear rate of the

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polycrystalline diamond composite (PDC) bit wear curve has been described in four different phases, i.e., break at entry, wear at layer of diamond, subsequent wear at the carbide layer's substrate and rapid break-down [7]. Furthermore, thermally stable polycrystalline diamond cutters for drill bits with low permissible brazing temperatures can reduce the thermal stress observed during drilling operations [8]. Measurements of drilling temperatures were essentially used to observe the bottom hole temperature during drilling [9]. During continuous drilling, the temperature gradient of the rock formation can be estimated using the bottom hole temperature. The primary observation in this regard is that the drilling rate increases conduction in the rock sample [10]. The wear rate of the drill bit was caused based on the abrasion of the rock sample. This is due to the silica (SiO_2) content of the rock sample. Hence, studying the rock characteristics would help in the selection of the optimum drilling parameters and type of drill bits [11]. In rotary drilling, the bit penetrates into metals, which is similar to that observed in case of rocks. In case of fine materials, low speed provides the best wear resistance, whereas for coarse-grained materials, high speed presents the best wear resistance [12]. Moreover, the tool wear can be measured using the weight difference method [13]. The wear rate of the bit is correlated to the textural properties of the rock samples, such as silica and quartz in the granite samples. Further, a linear relation was established for quartz and silica, with the wear rate of the drill bit [14]. The wear test results can also be compared to the estimation of the wear rate coefficient of the drill bit, which provides good precise observations for the abrasiveness of these materials [15]. For the influence of abrasive size on the cutting performance of concrete by means of an abrasive water jet experiment, it was found that a significant relationship exists between the cutting performance and uniaxial compressive strength [16]. For measuring the wear rates of the bit, the well-known Archard model has been successfully used in PDC and rock combination [17]. The SiO_2 content has a greater influence on the wear rate of the drill bit generally, an increase in the SiO_2 content of the rock samples leads to an increase in the wear rate of the bit [18].

In the present study, the rock drilling experiment was conducted using an embedded thermocouple technique for three different types of sandstone, taking into consideration their uniaxial compressive strength and the silica content of the rock sample. Moreover, the controlled parameters were considered such as drill bit diameter, spindle speed, and penetration rate in the test. The relation between the temperature produced at the bit-rock interface and the wear rate of the drill bit was examined. Wear rate of the drill bit were estimated using the mass loss method, and the wear rate coefficient of the drill bit was calculated for each type of the rock samples. The relationship between the bit-rock interface temperature and wear rate of the drill bit has also been discussed.

2 Experimental procedure

The rock drilling experiments were performed on a cylindrical sandstone samples of NX size (as per International Society of Rock Mechanics of diameter 54 mm and length 135 mm), which represents one of the sedimentary rock present in the rock formation. These experiments involved drilling the sandstone core sample on a CNC vertical drilling machine. Furthermore, three types of sandstones were used in these experiments: medium-grained sandstone (UCS 13.70 MPa), fine-grained sandstone (UCS 17.83 MPa), and fine-grained sandstone pink (UCS 51.67 MPa). All three types of these sandstones were 54 mm in diameter and 135 mm length (NX size). The experimental set-up comprised a chuck with controlled parameters such as spindle speed and penetration rate (Fig. 1). Moreover, a cutting tool dynamometer
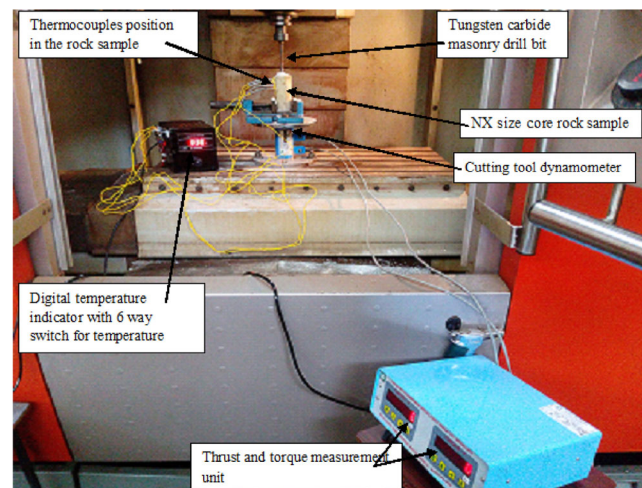
Fig. 1 Experimental set-up for temperature and thrust arrangement.

mounted on the CNC bed, along with a specially de-signed and fabricated grounded K-type thermocouple (0–1,200 °C), was fixed into the rock samples to measure the bit-rock interface temperature at a depth of 30 mm. This was done in such a way that the head of the thermocouple was placed 0.5 mm away from the bit-rock interface. In addition, the thermocouple wire was partially connected to the digital temperature indicator to acquire the temperature data [19]. Wear rate was measured for a few experimental com-binations by varying tungsten carbide drill bit diameter (6, 8, 10, 12, and 16 mm), spindle speed (250, 300, 350, 400, and 450 rpm), and penetration rate (2, 4, 6, 8 and 10 mm/min), the drilling has been carried out to measure the temperature [20, 21]. Under each drilling condition (bit diameter, spindle speed, and penetration rate), the drilling has been carried out for different drilling time (900, 450, 300, 225, and 180 s, respectively) to find out the average wear rate of a particular type of rock sample and corresponding interface temperature was measured [22, 23].

2.1 Measurement of the thrust

A cutting tool dynamometer was utilized to measure the thrust force. The dynamometer was fixed on the worktable, above which the vice is fixed. Between the jaws of the vice cylindrical rock sample was placed. The dynamometer, vice, and the rock sample lay on the same axis in such a way that the rock drilling experiment was performed (Fig. 1). This comprises full bridge strain gauge for force measurement. The outputs of this strain gauge bridges are available via a five-pin connector sockets present in the sensor body. The dynamometer was designed to force up to 5,000 N. The drilling force was measured at different drill bit diameters, as shown in Table 1.

Table 1 Specification of the drill bit used, along with the process parameter and their range.

Masonry drill bit	
Point angle	135°
Bit material	Tungsten carbide (WC)
Penetration rate	2, 4, 6, 8, and 10 mm/min
Spindle speed	250, 300, 350, 400, and 450 rpm
Drill bit diameter	6, 8, 10, 12, and 16 mm

2.2 Measurement of drilling temperature

Four K-type grounded thermocouples were situated vertically, one below the other, in the rock sample, as depicted in Fig. 2(a). The head of the thermocouple was placed 0.5 mm away from the bit-rock interface, as shown in Fig. 2(b). Moreover, the individual depths of the thermocouple were 6, 14, 22, and 30 mm, respectively, out of which the bit-rock interface temperature at 30 mm depth was measured to correlate with the wear rate of the drill bit.

2.3 Wear rate measurements

A series of drilling experiments was performed, during which the wear rate was measured for the regular intervals of known location. The mass loss method was employed to measure the wear rate of the drill bit by weighing it before and after the drill bit reached depth of 30 mm (Eq. (1)). To measure the bit weight, a digital weighing balance was used, with a resolution of 0.1 gm [5]. The majority of the losses occurred at the bit matrix and cutter head, because both of them were exposed to the rock [18].

Wear rate is calculated using the following Eq. (1).

$$\text{Wear rate} = \frac{\text{Mass loss}}{\text{Drilling time}} (\text{mg/s}) \qquad (1)$$

Archard equation is a model used to observe the abrasive characteristics of a tool based on the theory pertaining to the unevenness of surface contact. As per the Archard model, the following equations can be used to calculate the wear rate coefficient (k) in mm^3/(N·m). Hence, the equation can be written as $k = W/(L \cdot C)$, where W is the wear rate in mm^3, L is sliding length (m), C is the normal load (N) [23]. Finally
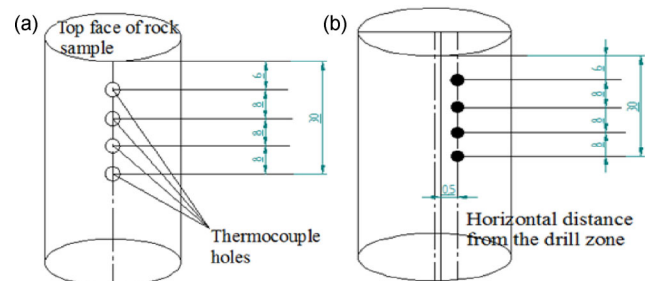
Fig. 2 (a) Front view of distance between the thermocouple holes, (b) hole and horizontal distance of sensor locations in the rock sample.

this equation can be rewritten as $k = W/(S \cdot N)$, where W is the wear rate (mg/s), S is spindle speed (m/s), N is the thrust (N), and the wear rate coefficient is given in Eq. (2).

$$K = \frac{W}{S \cdot N} (\mathrm{mg} / (\mathrm{N} \cdot \mathrm{m})) \qquad (2)$$

3 Results and analysis

3.1 Microstructure evolution and energy-dispersive X-ray spectroscopy (EDS) analysis

Scanning electron microscope (SEM) micrograph analysis was conducted for three types of rock samples, i.e., medium-grained sandstone, fine-grained

sandstone, and fine-grained sandstone pink, as explained in Fig. 3. Furthermore, EDS analysis was carried out to determine the weight percentage of the silica content in the rock samples, as shown in Table 2. The silica content of the rock sample and wear rate summary of the bits and rock combinations are shown in Table 3.

Table 2 Chemical composition (wt%) of medium-grained sandstone (MG), fine-grained sandstone (FG), and fine-grained sandstone pink (FGP).

Element	O	Mg	Al	Si	K	Ca	Ti	Fe	C
MG	39.22	0.24	4.90	**7.30**	0.28	0.23	0.66	0.74	14.74
FG	65.96	0.27	10.91	**16.45**	—	—	0.63	5.24	24.76
FGP	54.34	—	3.76	**30.22**	—	0.27	—	—	20.40
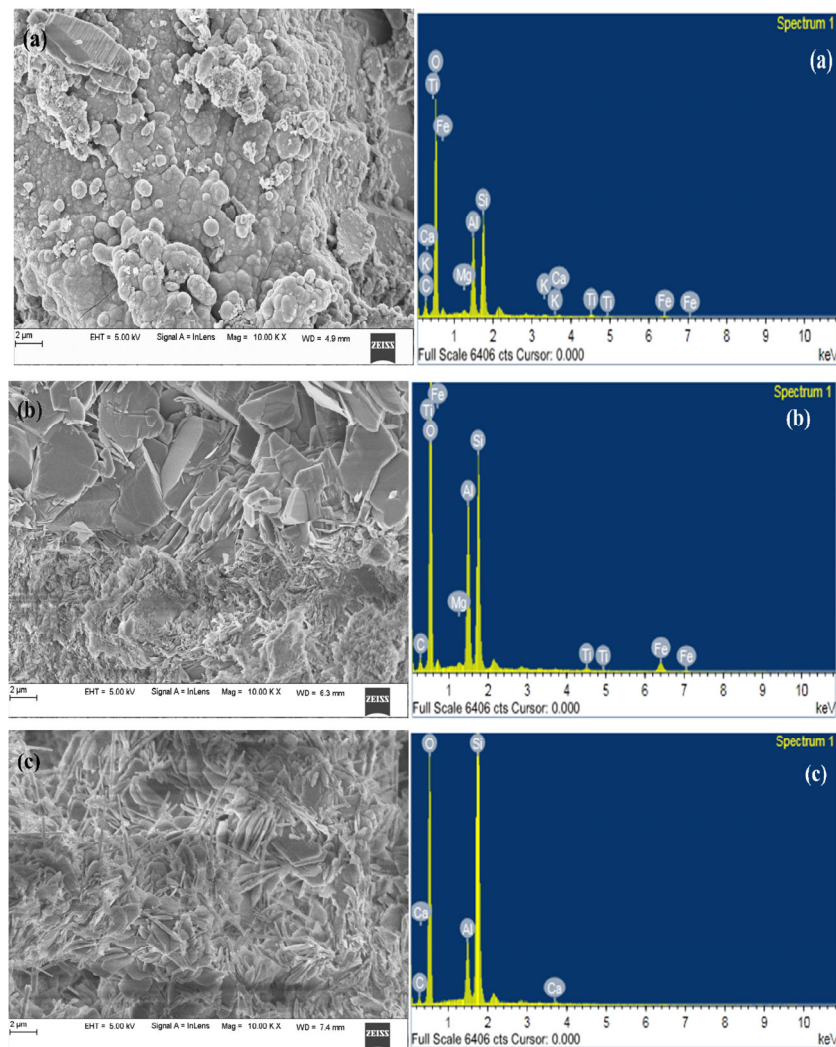
Fig. 3 SEM micrographs and EDS analysis of (a) medium-grained sandstone, (b) fine-grained sandstone, and (c) fine-grained sandstone pink.

Table 3 Factors effecting on bit-rock interface temperature, silica content, and wear rate summary of three types of sandstone.

Test (No.)	Rock type	Operational parameters			Bit-rock interface temperature (°C)	Silica (wt%)	Weight of bit (gm)		Wear rate (mg/s)	Uniaxial compressive strength (MPa)
		Drill bit diameter (mm)	Spindle speed (rpm)	Penetration rate (mm/min)			Before drill	After drill		
1		6	250	2	51		36	35	1.111	
2		8	300	4	68		54	53	2.222	
3	Medium-grained sandstone	10	350	6	74	7.30	86	84	6.666	13.70
4		12	400	8	86		109	106	13.333	
5		16	450	10	91		156	152	22.222	
6		6	250	2	58		35	33	2.223	
7		8	300	4	66		53	50	6.667	
8	Fine-grained sandstone	10	350	6	83	16.45	84	80	13.333	17.83
9		12	400	8	106		107	102	22.223	
10		16	450	10	128		154	148	33.333	
11		6	250	2	96		34	31	3.334	
12		8	300	4	116		51	46	11.112	
13	Fine-grained sandstone pink	10	350	6	148	30.22	82	76	20.010	51.67
14		12	400	8	166		105	98	31.112	
15		16	450	10	236		151	143	44.445	

3.2 Effect of UCS and SiO₂ of the rock on wear rate of the drill bit

Knowledge pertaining to rock properties and textural characteristics is important for bit design and operational conditions. In this experiment, uniaxial compressive strength and the SiO_2 present in the rock samples are identified to correlate with the wear rate of the tungsten carbide (WC) drill bit. Moreover, the strength of the rock samples mainly depends on the Moh's hardness of the mineral present in the rock samples. Abrasive wear is primarily composed of hard mineral. The Moh's hardness of a mineral that is more than 5.5 can be classified as abrasive (causing a high level of abrasive wear) [24]. Hence, SiO_2 has the second highest Moh's hardness with a value of 7 [18]. Sandstones with high quartz content possess higher strength properties in comparison to those with lower quartz content [25]. Three different SiO_2 of varying wt% were observed in the sandstone using EDS analysis, and the strength of the rock samples in terms of UCS has been shown in Table 4. This occurs owing to the friction between the rock and the drill bit, which depends on the silica content of the rock sample; so

does the hardness of the rock sample increases [26], which has been demonstrated in Fig. 4.

Table 4 Average wear rate of drill bit corresponding to UCS and SiO_2 of the rock samples.

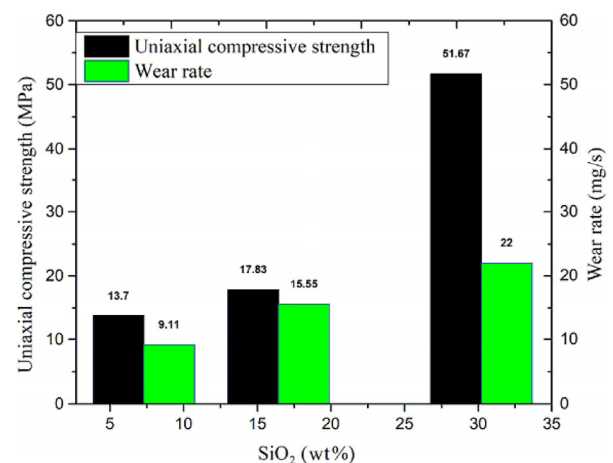| Rock type	UCS (MPa)	SiO_2 (wt%)	Average wear rate (mg/s)
MG	13.70	7.30	9.11
FG	17.83	16.45	15.55
FGP	51.67	30.22	22.00

Fig. 4 Correlation of SiO_2 vs. wear rate and uniaxial compressive strength of the rock samples.

Figure 5 shows the effect of thrust on the wear rate of the drill bit. It is ascertained that the thrust increases with an increase in the wear rate of the drill bit. This is because the resistance offered by the rock samples as well as the force required by the drill bit to drill the rocks increase [26].

Subsequently, Fig. 6 shows the effect of temperature on the wear rate of the drill bit. It is found that medium-grained sandstone contains 7.30 wt% of silica observed at 91 °C, whereas fine-grained sandstone contains 16.45 wt% of silica observed at 124 °C, and fine-grained sandstone pink contains 30.22 wt% of silica observed at 236 °C. Furthermore, SiO_2 has a high Moh's hardness value of 7 [18]. In addition, SiO_2 results in a ploughing effect that can increase the mechanical force and friction coefficient [26]. Hence, it can be clearly understood that as the silica content of the rock samples increases, heat is transferred between the bit-rock interfaces increases [6]. Moreover, as the drill bit diameter increases from 6 to 16 mm, the volume of rock removal also increases. Thus, the contact area of the bit-rock interface increases, which leads to an increase in the frictional force. The effect of drill bit diameter on its wear rate has been shown in Fig. 7.

Rock formation characteristics have a significant increase in wear temperature [6]. Strength of a rock is defined by means of a SiO_2 percentage and generally has a high Moh's hardness value. However, wear rate measurement of the WC bit involves material loss
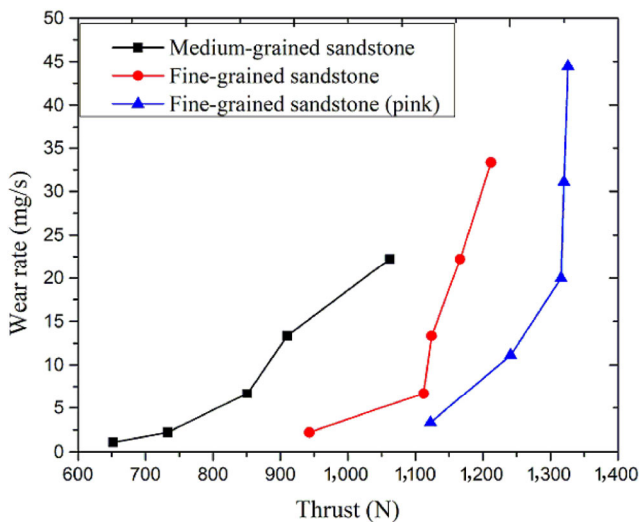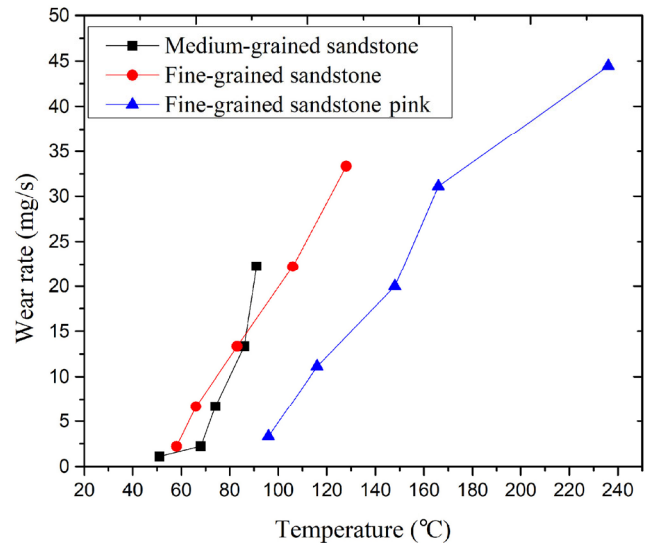

Fig. 6 Effect of bit-rock interface temperature on the wear rate of the drill bit.
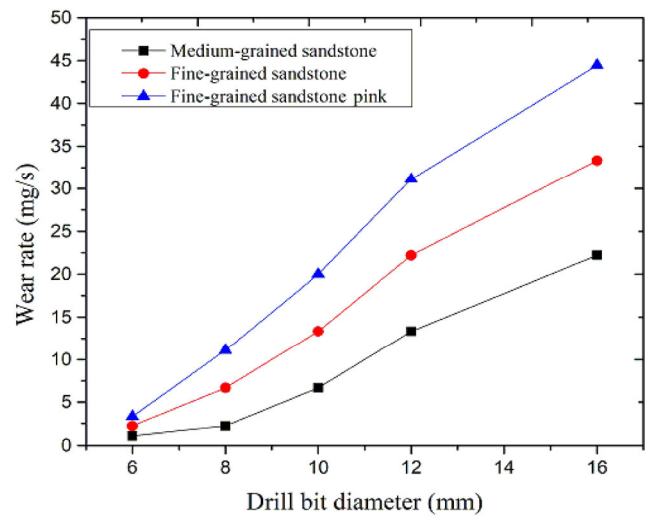

Fig. 7 Effect of drill bit diameter on the wear rate of the drill bit.

under fixed speed for constant distance. The Archard model is applied for tribological studies owing to its correlative linear equation between material loss (mg) and the load (N) acting per unit distance (mm). Further, its units are expressed in mg/(N·m) and is shown in Fig. 8.

3.3 Statistical analysis

Simple linear regression analyses were conducted for the three types of sandstone. The results of the relationship between bit-rock interface temperature and the wear rate have been presented in Eqs. (3)–(5).

Fig. 5 Effect of thrust on wear rate of the drill bit.
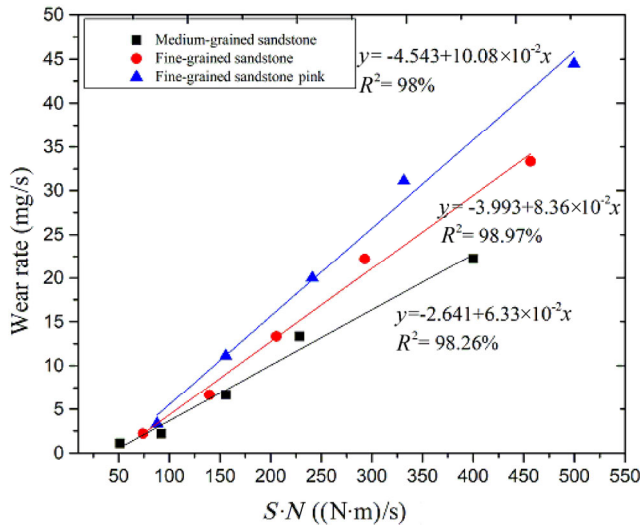
Fig. 8 Wear rate of the WC drill bit as a function of the product of S and N to estimate its wear rate coefficient.

Moreover, the statistically significant mathematical models have been tested through the ANOVA and R^2, and the value of R^2 that is near to 100% can lead one to assert that the obtained model is adequate, as shown in Table 5. Statistical equations (Eqs. (3)–(5)) clearly show that the independent variables are statistically significant, with P-values that are less than 0.05, as depicted in Table 6. The regression analysis further shows that the error between the experimental and predicted values is less than 10%, which has been shown in Table 7. Hence, the predicted models are reasonably accepted within the expected range.

$$\text{WR}_{MG} = -27.90 + 0.500 \times T_{MG} \qquad R^2 = 81.19\% \qquad (3)$$
$$\text{WR}_{FG} = -22.49 + 0.431 \times T_{FG} \qquad R^2 = 98.69\% \qquad (4)$$
$$\text{WR}_{FGP} = -23.02 + 0.295 \times T_{FGP} \qquad R^2 = 96.64\% \qquad (5)$$

Table 5 ANOVA for the dependent variables of the three types of rock samples.

Source	F-value	P-value
Temperature (T_{MG})	12.950	0.037
Temperature (T_{FG})	948.65	0.000
Temperature (T_{FGP})	86.280	0.003

Table 6 Statistical analysis results of the significant regression models.

Model	Variables	Coefficient	Standard error	T-value	P-value
		MG			
Eq. (3)	Constant	−27.90	10.5	−2.66	0.076
	T_{MG}	0.500	0.139	3.60	0.037

(Continued)

Model	Variables	Coefficient	Standard error	T-value	P-value
		FG			
Eq. (4)	Constant	−22.49	1.29	−17.48	0.000
	T_{FG}	0.431	0.014	30.80	0.000
		FGP			
Eq. (5)	Constant	−23.05	5.09	−4.53	0.020
	T_{FGP}	0.295	0.031	9.29	0.003

Table 7 Measured and predicted wear rate of the WC drill bit for different types of rock sample.

Rock type	Measured wear rate (mg/s)	Predicted wear rate (mg/s)	Average error (%)
MG	1.111	1.578	
	2.222	6.111	
	6.666	9.111	7.559
	13.333	15.109	
	22.222	17.609	
FG	2.222	2.527	
	6.666	5.978	
	13.334	13.312	1.194
	22.222	23.234	
	33.334	32.725	
FGP	3.333	4.324	
	11.111	11.240	
	20.001	20.699	
	31.111	26.020	4.624
	44.444	46.711	

4   Conclusions

From the aforementioned experimental work, the bit-rock interface temperatures of three types of sandstone are investigated, in order to identify the wear rate of the WC drill bit using the mass loss method, and the following conclusions are drawn:

1) A significant relationship exists between wear rate and bit-rock interface temperature, which is essential to understand the thermal environment of rock samples.

2) The average bit-rock interface temperature for MG, FG, and FGP is 74, 88, and 152 °C, respectively. Further, the corresponding average wear rate is 9.111, 15.554, and 22.001 mg/s, respectively.

3) The wear rate of the drill bit is primarily influenced by bit-rock interface temperature. From the ANOVA analysis of the three types of rock samples, it is observed that the temperatures are significant, and *P*-value is lest than 0.05.

4) For the wear rate coefficient determined from the value obtained through experimental analysis using the Archard model, it is observed that the wear rate coefficient increased with an increase in the bit-rock interface temperature. This is due to the increase in SiO_2 (wt%) and the uniaxial compressive strength of the rock samples.

5) From the SEM and EDS analysis, it is clear that MG sandstone contains large grain particles that are weakly bonded and have less SiO_2 content of 7.85 wt%, which gives a less wear rate coefficient of 6.33×10^{-2} mg/(N·m) and has a minimum bit-rock interface temperature of 74 °C. Similarly, FG contains 16.45 wt% silica content gives wear rate coefficient of 8.36×10^{-2} mg/(N·m), and FGP contains 30.22 wt% silica content gives wear rate coefficient of 10.08×10^{-2} mg/(N·m), respectively.

6) The proposed simple linear regression models for the wear rate of the WC drill bit correlate reasonably well with the experimental data.

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