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Study of Effect of Cooling/Lubricating Fluids, Machining Parameters, and Rock Mechanical Properties on Penetration Rate in Rock Drilling Process

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Abstract

In most rock drilling operations, the low rate of penetration (ROP) can be primarily attributed to the presence of the cuttings produced during drilling and the thermal stresses caused by friction at the bit-rock interface, which can be exacerbated with the increasing strength, hardness, and abrasivity of the drilled rock. In order to improve ROP, drill bit lifetime, and cutting power, it is necessary to minimize the process forces due to the mechanical bit-rock interaction and the thermal stresses generated in the drill hole. Any improvement in these areas is extremely important from both the technical and the economic perspectives. This improvement can be achieved by the use of appropriate cooling/lubricating fluids in the drilling process in order to increase ROP, reduce the temperature of the drilling environment, and create a clean drill hole free of cuttings. In this work, a series of laboratory drilling tests are performed to investigate and compare ROP in the drilling of seven samples of hard and soft rock in the presence of six different cooling-lubricating fluids. The drilling tests are performed on the cubic specimens with a laboratory-scale drilling rig at several different rotation speeds and thrust forces. The statistical analyses are performed in order to investigate the relationship between ROP and the mechanical properties of the rock, properties of the fluid, and machining parameters of the drilling rig. These analyses show that under similar conditions in terms of mechanical properties of the rock using Syncool with a concentration of 1:100 and soap water with a concentration of 1:120 instead of pure water leads to the average 31% and 37% increased ROP in granite, 36% and 43% increased ROP in marble, and 47% and 61% increased ROP in travertine, respectively. These results demonstrate the good performance of these cooling/lubricating fluids in increasing ROP.

1. Introduction

Drilling is an engineering operation with a wide range of applications in a variety of fields including mining engineering, oil engineering, civil engineering, groundwater withdrawal, etc.[1]. Given the typically high cost of the drilling operations and drilling rigs, the engineers and operators need to have a sufficient knowledge of all the parameters involved in the drilling process and how they can be optimized for cost minimization [2, 3]. The performance enhancement of diamond drilling operations can have a notable impact on the economy of mining operations by increasing the Rate Of Penetration (ROP), improving the drill bit lifetime and wear rate, decreasing the energy consumption, and generally, reducing the drilling costs. This enhancement can be done by a proper use of appropriate cooling and lubricating fluids in the drilling process [4]. Given the extensive use of the diamond drilling technology, a wide range of drilling coolants and lubricants are used in this area. The main purpose of lubricants is to reduce the rotational friction between the drill bit and the rock face. In other words, the drilling fluids are used to reduce the frictional resistance at the bit-

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rock interface in order to improve the drilling efficiency and ROP and prolong the drill bit lifetime [5]. Over the years, many researchers have explored a variety of ways whereby the efficiency of drilling operations could be improved. One of these methods is to use the chemical additives to affect the surface properties of the rock being drilled. There are reports showing that adding these chemicals to the drilling fluid can increase the drilling rate by up to 90%. The reported improvement rates vary significantly with the type of drilling rig, nature of the drilled rock, type and rotation speed of the drill bit, and thrust force (force applied behind the drill) as well as the chemical factors such as the pH of drilling fluid, zeta potential of minerals, and concentration of the chemical agent. There are also some inconsistencies in the reported improvements [6]. In a series of studies conducted by Rehbinder et al. (1944) on the change in the hardness of rock after adding chemicals to the drilling fluid, they investigated the effect of adding electrolytes on the drilling rate in rocks such as granite and quartzite, ultimately reporting improvements in the range of 20-80% [7]. In the early 1960s, Dauncey published a report on the use of cooling additives in drilling with diamond bits, which confirmed the positive effect of these additives, especially when drilling in hard rocks. The results of the Dauncey's tests showed that in addition to increasing ROP, these additives significantly improve the drill bit performance and lifetime as well as its post-extraction condition [8]. In 1963, Hammond and Ravitz investigated the effect of using chemical additives in the drilling fluid on the drilling rate in limestone. These researchers reported that adding sodium citrate to water instead of using pure water without additives in the drilling of Indiana limestone in the United States led to a 25% resistance reduction and an improved drilling rate [9]. In 1969, Salim et al. experimentally investigated the effect of adding organic additives to water on the performance of diamond bit in quartzite. This experiment showed that using the additives in the drilling fluid increased ROP and decreased the torque, friction coefficient, and wear rate [10]. In a 1976 study by Cooper and Berlie on the effect of coolant/lubricant fluids on the drilling performance, the results obtained showed that none of the additives had a significant effect on ROP but using them instead of pure water (without any additive) significantly reduced the bit wear rate [11]. In 1978, Mills and Westwood investigated the effect of chemo-mechanically active fluids on the drilling performance in hard rocks. The tests of these researchers showed that the chemo-mechanically active fluids reduced the wear rate of diamond bit and increased the drilling rate [12]. In 1996, Langwei investigated the lubrication mechanism of diamond bits with drilling fluids. The tests of this study were conducted with water and sodium oleate solution (a combination of oleate fatty acid with sodium ions) as the drilling fluids. The results of these tests showed that sodium oleate solution had a good cooling and lubricating effect, which reduced the frictional resistance at the bit-rock interface, and also improved the bit wear rate and ROP [5]. In a 2000 study by El-Shallet et al. on the effect of the coolant/lubricant additives on hard rock drilling, the results obtained showed that the use of chemical additives in the fluid increased the drilling rate [13]. In 2002, Rao et al. conducted extensive laboratory studies on the effect of drilling rig operating parameters on the drilling performance when PEO (polyethylene oxide) was added to water as a coolant/lubricant additive. The test results showed that the torque was approximately 1.5 times lower when the fluid contained PEO than when it was pure water [14]. In 2009, Messaoud investigated the effect of the coolant/lubricant fluids on the drilling performance, ultimately reporting that at a constant drill rotation speed, ROP increased with the use of coolant/lubricant instead of pure water as well as increasing the thrust force [15]. In 2010, Bhatnagar et al. conducted a series of tests to improve the performance of diamond drilling by using the mixtures of non-ionic polymers and water as the cooling/lubricating fluid. The results obtained showed that for all the drill rotation speeds and thrust forces, using the additive-containing fluid instead of pure water led to an increased ROP [16]. In a 2011 study by Zhao et al. on the effect of mineral salt additives and surfactants on ROP in sandstone, the results obtained showed that using the additive-containing fluid increased ROP [4]. In 2011, Bhatnagar et al. also conducted a laboratory study to investigate the effect of using PEO as coolant/lubricant in diamond drilling of marble. In this study, these researchers investigated the effect of coolant on ROP and torque under a variety of thrust forces and drill rotation speeds. The results of laboratory tests showed using the additive-containing fluid increased ROP, and reduced the torque [17]. In 2012, Bhatnagar and Khandelwal investigated the effect of the drilling rig operating parameters on ROP as one of the main measures of drilling performance. In this study, an artificial neural network was used to construct a model for predicting ROP based on the operating parameters [18]. In a 2015 laboratory study conducted by Wei Lee et al. on the effect of surfactants of different concentrations on ROP in rotary diamond drilling, the results obtained showed an increase in ROP, which was found to be associated with the concentration of surfactants [19]. In 2016, Rohit et al. investigated the effect of adding three polymeric additives to water instead of using pure water on ROP in sandstone drilling. These researchers reported that using certain concentrations of these additives improved the drilling performance in terms of ROP and friction at the bit-rock interface [20]. In the same year, Taheri et al. introduced an index for predicting ROP based on a series of parameters including the uniaxial compressive strength of the drilled rock. This index has been formulated such that as it increases, ROP decreases [21]. In a 2018 study by Wang and Li, they developed a model for predicting the drill bit wear rate and rock abrasivity. This model showed that the wear rate and drilling performance were influenced by the following rock properties (in the order of effect size): elastic modulus, quartz content, internal friction angle, surface roughness, Poisson ratio, and cohesion [22]. In another study published in 2018, Shad et al. investigated the effect of physical and mechanical parameters of rock on ROP in iron ore drilling. The results of this study showed that the rocks with higher hematite content than magnetite content tend to have a higher wave velocity, which indicates a lower drilling rate [23]. In another 2018 article, Xiao et al. studied the performance of a rotary drilling system and the bit-rock interaction by recording the elastic waves generated by the drilling rig and the bit during drilling. The results of this study showed an increase in the drilling performance with the decrease in the seismic wave amplitude and frequency bandwidth [24]. In 2020, Shankar et al. studied the relationship between thermal stresses at the bit-rock interface and the wear rate of the tungsten carbide drill bit during rotary drilling. The results of linear regression analysis showed that the wear rate increased with increasing temperature at the bit-rock interface [25]. In the same year, Piri et al. published a study where they compared the effect of three types of drill bit coatings on the bit wear rate and then examined how this wear rate was affected by the physical and mechanical properties of drilled rock and tool specifications [26]. In another 2020 study, Liao et al. tried to determine the suitable features for ROP prediction and optimization with an artificial neural network. The results of this study showed that such intelligent techniques could be used to construct useful models for predicting ROP and optimal drilling conditions [27]. In another article published in 2020, Feng Shangxin et al. tried to estimate the optimal drilling efficiency and rock strength for rotary drilling by the use of controllable drilling parameters. This article reported that there was a linear relationship between the thrust force and ROP, the slope of which depended on the rock properties [28]. In 2021, Kolapo studied the effects of the mechanical properties of five rock samples on ROP. The results obtained showed that ROP decreased as the uniaxial compressive strength increased and there was a linear relationship with a high correlation coefficient between the mechanical properties of the rock and ROP [29]. In another 2021 study, Lawal et al. used the statistical models and artificial neural networks to predict ROP in rock drilling [30]. Recently, Piri et al. (2021) have examined the effect of drill bit coating on the level of noise created during hard rock drilling. These researchers reported that the noise level generated in drilling environments could be a good predictor of the physical and mechanical properties of the drilled rock, hardness of the drill bit, and operating specifications [31].

From the above review of studies on ROP and the effect of coolant/lubricant on the drilling performance, it could be concluded that most of these studies had investigated the effect of drilling rig operating parameters on the drilling performance in the presence of coolant/lubricant, overlooking how the drilling performance could be affected by the physical properties of coolant/lubricant and how this effect could be influenced by the physical-mechanical properties of the rocks being drilled. Given the great importance of ROP for decreasing the drilling costs and increasing drilling rate and efficiency, in this work, we investigated the simultaneous effect of mechanical properties of the drilled rock (uniaxial compressive strength, Young's modulus, Mohs hardness, and Schmiazek abrasivity factor), properties of the coolant/lubricant fluid (pH, viscosity, and conductivity), and operating the parameters of the drilling rig (thrust force and drill rotation speed) on ROP.

2. Methodology

This work consists of two phases: a field study phase, which involves selecting, collecting, and preparing the rock samples and also the samples of coolant/lubricant fluids, and a laboratory testing phase, which involves transferring the samples to the laboratory, preparing specimens for the tests of mechanical properties (for rocks) and physical properties (for fluids), building a laboratory-scale drilling rig capable of measuring and recording ROP, and conducting the laboratory-scale drilling tests. A flowchart of the research process is shown in Figure 1.

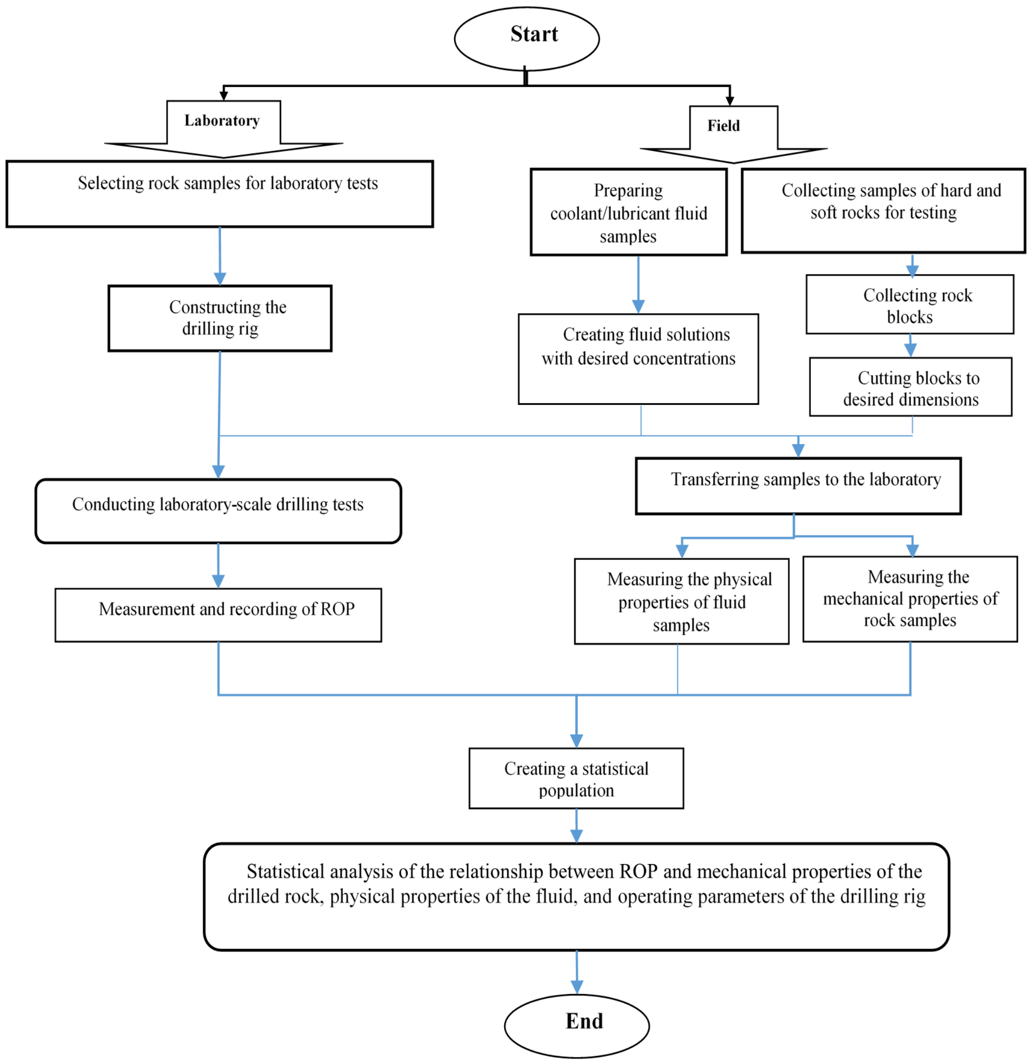


Figure 1. A flowchart of the research process.

3. Field and laboratory studies

The merging laboratory tests with field studies is known to improve the internal and external validity of the research work. While the field studies that are carried out under natural conditions with the least human interference often have a higher external validity, they also tend to be more expensive and have a lower internal validity due to the lack of control over potentially effective variables. Meanwhile, performing the laboratory tests under controlled conditions allow us to eliminate the effect of interfering factors and carefully examine the effect of a variety of target variables on the studied phenomenon by making as many changes as required in the test procedure and conditions.

3.1. Field phase

The selection of rock samples is a particularly important part of the studies conducted in the mining industry. Since the selected samples represent a slab, a block or on a larger scale a deposit, the quality of the results of the laboratory studies strongly depends on how these samples are selected and prepared for testing. In this research work, after studying the literature in the field of rock drilling and cooling/lubricating fluids, the authors visited several quarries and stone-cutting factories in order to collect the desired samples (Figure 2). The list of sampled rocks and stones and their type and brand name is provided in Table 1. The locations of the sampled mines are presented in Figure 3.

(a) (b) (c)

Figure 2. a-b-c). Rock sampling procedure.

Table 1. Name and brand of collected rock samples.

T	Name of quarry	Commercial name	No.
Hard	Sefid Natanz	Granite	A1
Hard	Khoramdare	Granite	A2
Hard	Khoshtinat	Granite	A3
Soft	Salsali	Marble	A4
Soft	Harsin	Marble	A5
Soft	Hajiabad	Travertine	A6
Soft	Azarshahr	Travertine	A7

After reviewing the previous studies on the cooling/lubricating fluids, the fluids that offered the best cooling/lubricating properties when mixed with water in different concentrations were selected (Figure 4). The list of these fluids, their brand name, and the abbreviation chosen for their samples is provided in Table 2.

Figure 3. Location of sampled quarries.

(a) (b) (c)

Figure 4. Specifications of chosen fluids: a) Soap water b) Syncool c) Boron nitride powder.

3.2. Laboratory phase

The laboratory phase of this work involved transferring the collected rock samples to the rock mechanics laboratory, preparing the specimens for tests of mechanical properties (for rocks) and physical properties (for fluids), and ultimately, conducting the drilling tests with a researcher-made laboratory-scale drilling rig using different cooling/lubricating fluids. In the first stage of the laboratory phase, the chosen rock blocks, which included three samples of hard rock and four samples of soft rock, were cut in the dimensions suitable for the laboratory tests, measurements of the physical and mechanical properties, and the drilling tests performed in the rock mechanics laboratory.

The following four mechanical properties of the rocks were measured with standard tests:

(a) Uniaxial Compressive Strength (UCS)

(b) Schmiazek abrasivity factor (SF-a)

(c) Young's Modulus (YM)

(d) Mohs Hardness (MH)

When selecting the rock samples for the laboratory tests, an utmost effort was made to collect the samples that would be large enough to provide enough material for all tests. The samples that had signs of fracture and alteration were discarded, and the collected blocks were also examined for the macroscopic defects. In the next stage, the mentioned properties were measured with standard tests as instructed by ISRM [32].

The uniaxial compressive strength was measured using the standard method instructed in C175. In this method, the jaws of the compression machine apply an increasing pressure to the cubic sample until fracture [33]. For this measurement, a diamond core drill was used in order to take five standard specimens with a length to diameter ratio of 2.5:1 from each block. The cores obtained were fully polished and then put inside the compression machine, where they were subjected to a stress of 1-1.2 MPa until fracture. Finally, the average uniaxial compressive strength of each rock sample was calculated from the measurements.

The Schmiazek abrasivity factor of the rock samples is given by Equation 1 [34].

$$SFa = \frac{EQC \times Gs \times BTS}{100} \quad (1)$$

where F is the Schimazek's wear factor (N/mm), EQC is the equivalent quartz content percentage, Gs is the median grain size (mm), and BTS is the indirect Brazilian tensile strength.

The average hardness of the rock samples was determined based on the hardness of the minerals contained in the rock. For this purpose, after determining the relative amount of each mineral in the rock with the help of thin sections, its average hardness was calculated using Equation 2 [34].

$$Mean\ \ Hardness = \sum_{i=1}^{n} M_i \times H_i \quad (2)$$

where Mi is the mineral amount (%), Hi is Mohs hardness, and n is the total number of minerals in the dimension stone.

For elastic modules, in this work, we used the Young's tangent modulus, which is the slope of the line tangent to the axial stress-strain curve at a point with 50% of the final strength. The results of the rock mechanics laboratory tests of the studied rock samples are presented in Table 3.

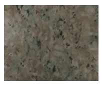
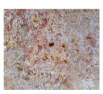
Table 2. Brand, concentration, and abbreviation of chosen fluids.

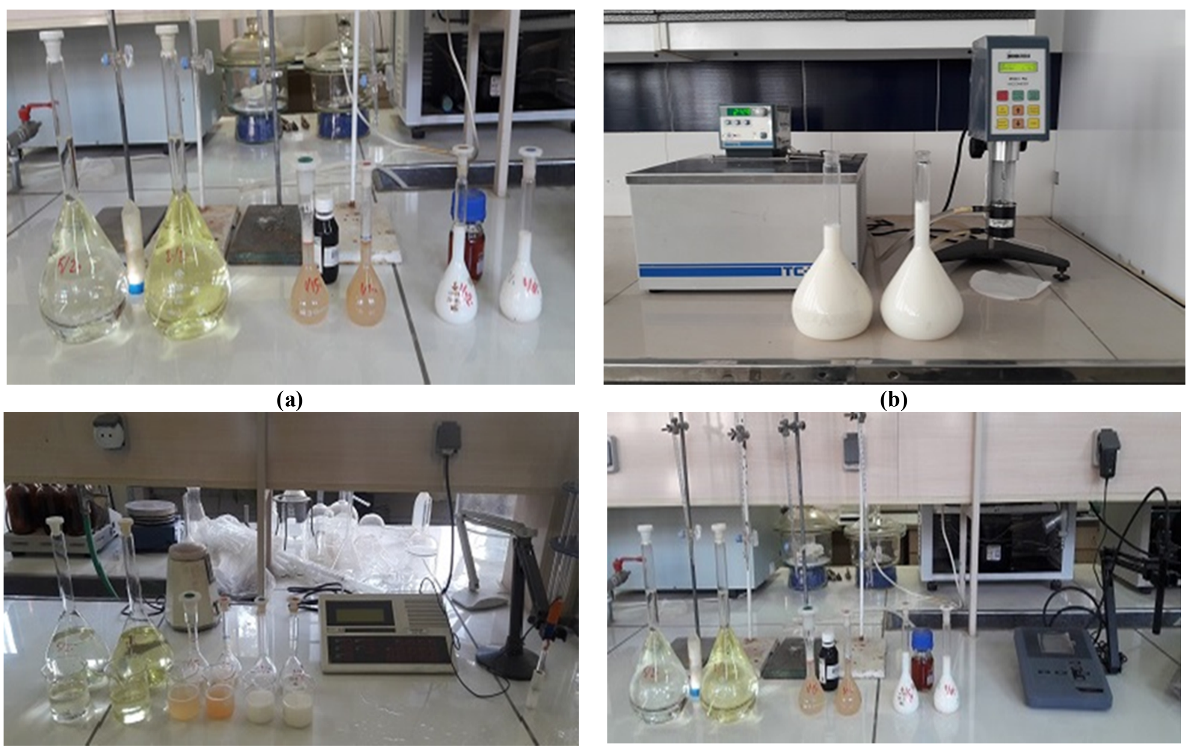
Abbreviation	Name/Brand	No.
FW	Water	B_1
FSW_1	Soap water with a concentration of 1/60	B_2
FSW_2	Soap water with a concentration of 1/120	B_3
FS_1	Syncool with a concentration of 1/100	B_4
FS_2	Syncool with a concentration of 1/150	B_5
FBN	Boron nitride powder with a concentration of 5/20	B_6

All concentrations are in the liters of additive solved in the specified liters of water

In the next stage of the laboratory phase, after transferring the coolant/lubricant samples to the laboratory and determining their best concentrations for the intended application, the samples were subjected to the laboratory tests in order to determine their pH values, viscosity, and conductivity (Figure 5). In this work, six fluids were used to perform the drilling tests on the blocks prepared from seven rock samples. The results of the laboratory tests of the physical properties of the studied fluids are presented in Table 4.

Table 3. Important mechanical properties of studied rocks.

Dimension stone sample		Commercial name	Name of quarry	UCS (MPa)	SF-a (N/mm)	YM	MH
A_1		Granite	Sefid Natanz	154	13.54	43.4	5.74
A_2		Granite	Khoramdare	141	11.2	36.5	5.65
A_3		Granite	Khoshtinat	132	10.26	28.8	5.47
A_4		Marble	Salsali	68.03	0.105	31.45	3.08
A_5		Marble	Harsin	71.53	0.136	32.51	3.6
A_6		Travertine	Hajiabad	61.48	0.125	21.05	2.9
A_7		Travertine	Azarshahr	52.96	0.122	19.81	2.89



(a) (b) (c) (d)

Figure 5. a) Preparation of fluids in the target concentrations, b) viscosity measurement, c) pH measurement, d) EC measurement.

Table 4. Physical properties of studied fluids.

Fluid sample	Commercial name	Density of fluid	Vis. (mPa.S)	PH	EC (μs/cm)
B_1	Water	-	1.012	7.65	386
B_2	Soap water	1/60	1.312	9.25	147.3
B_3	Soap water	1/120	1.295	9.81	102.5
B_4	Syncool	1/100	1.381	9.39	166.4
B_5	Syncool	1/120	1.196	8.86	152.8
B_6	Boron nitride powder	5/20	8.17	8.17	238.9

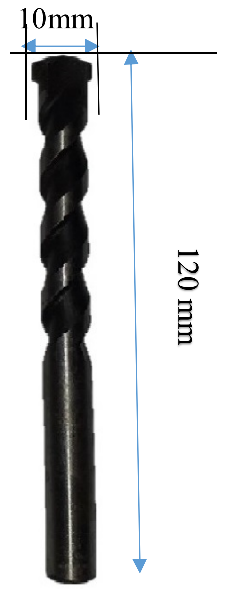
3.3. Construction of drilling rig

A common flaw of many studies that examine the drilling parameters in different rock samples is that they collect the required data from different mines, which tend to have different drilling rigs and tools as well as different operating conditions. Thus due to the heterogeneity of the data collected from different mines, the results of their analyses are either highly uncertain or completely unreliable. In order to avoid this problem, in this work, we attempted to ensure the homogeneity of the data used in the analysis of the effect of coolant/lubricant on the drilling parameters by designing and fabricating a laboratory-scale drilling rig in line with the research objectives.

The fabricated drilling rig consists of two main components: a drill component, which is responsible for drilling the rock, and a processor component, which is tasked with controlling and recording the drilling data. In order to perform a drilling test, the necessary instructions regarding the rotation speed and flushing condition must be given to the system through a touch screen panel. The thrust force to be applied to the test specimen can be adjusted by changing the weights suspended on the side of the rig with a chain and gear system. Upon launch, the system starts drilling the rock according to the provided instructions, while also measuring ROP, torque, power consumption, and fluid flow rate, and stores the collected data in a file. The specimens are required to be fixed on a circular plate, which can be moved vertically according to the rig conditions. The specimens must be fully secured with a clamp mounted on the circular plate to prevent movement during the drilling test. Also four leather covers were installed beneath the rig in order to prevent vibrations and ensure that the rig remained stable. The cooling/lubricating fluid was pumped through a chamber positioned at the bottom of the rig and then sprayed on the specimens by the rig's flushing system, which was positioned next to the bit. This flushing system could move in all directions, and was equipped with a valve that could be adjusted to reach the desired fluid flow rate during the test. After cutting the blocks of required sizes from all the collected rock samples, they were transferred to the location of the drilling rig for the laboratory drilling tests. The drill used in this work was a tungsten carbide bit with a diamond blade designed for drilling in hard rocks such as granite. The diameter of the bit was 10 mm. For each block, the drill points were positioned on the centerline with a spacing of at least 30 mm (more than twice the bit diameter). Figure 6 shows a view of the drilling rig, the chosen drill bit, and the rock specimens prepared for the drilling test.

The drilling test of this work aimed to investigate the effect of the drilling rig operating parameters, mechanical properties of the drilled rock, and physical properties of coolant/lubricant on ROP. For these tests, the cuboid rock specimens with approximate dimensions of 10 × 10 × 15, 10 × 10 × 20, and 10 × 10 × 30 were prepared. Since the drill rotation speed and the thrust force were adjustable, first, several tests were performed at maximum and minimum powers in order to determine the suitable rotation speed and thrust force for drilling in the hard and soft specimens and identify the configurations where excessively low or high speed and thrust caused the bit to get stuck or even break. After a number of trials and errors on the hard and soft rock specimens, it was decided to use the rotation speeds of 1190, 1057, and 933 rpm and thrusts of 133, 116, 95, and 77 kg for the hard rocks and the rotation speeds of 933, 845, 720, and 610 rpm and thrusts of 116, 95, 77, and 58 kg for the soft rock specimens. All tests were performed with the same type of drill bit. In order to determine an appropriate fluid concentration for different operating conditions, the soft rock samples (A_4, A_5, A_6, A_7) were drilled with water and the five cooling/lubricating fluids (FS_1, FS_2, FSW_1, FSW_2, and FBN). After reviewing the results obtained, two of these fluids that offered the highest ROP were selected for use in the drilling of hard rock specimens. Therefore, for the hard rock specimens (A_1, A_2, A_3), the drilling tests were performed with FS_1 and FSW_2 as well as pure water. The number of tests performed on the soft rock specimens was 64 per fluid or 384 in total. The number of tests performed on the hard rock specimens was 36 per fluid or 108 in total. Thus a total of 492 tests were conducted to investigate the relationship between ROP and the mechanical properties of the drilled rock, physical properties of the fluid, and operating parameters of the drilling rig in the drilling of seven types of hard and soft rock specimens (with three fluids for the hard rocks and six fluids for the soft rocks).

(b)



(a)

(c)

Figure 6. a) Fabricated drilling rig, b) drill bit used in drilling test, c) rock specimens prepared for drilling test.

4. Statistical analysis

The univariate linear regression method was used in order to find the relationship between ROP and the mechanical properties of the drilled rock, physical properties of the fluid, and operating parameters of the drilling rig. First, the relationship between the mechanical properties (i.e. UCS, SF-a, MH, and YM) of granite, marble, and travertine samples and ROP in the presence of FW, FS_1, and FSW_2 under constant operating conditions of 77 Kg thrust and 933 rpm rotation speed was analyzed with linear, power, exponential and logarithmic functions, and the function offering the highest correlation coefficient was determined.

As the diagram of Figure 7 shows, there is a strong exponential/power relationship between UCS of the drilled rock and ROP. This relationship follows an exponential function with a correlation coefficient of $R^2 = 0.82$ in the presence of FW, a power function with a correlation coefficient of $R^2 = 0.92$ in the presence of FS_1, and a power function with a correlation coefficient of $R^2 = 0.89$ in the presence of FSW_2 as the coolant/lubricant fluid. The general trend of this relationship suggests that, as expected, a higher UCS leads to a decrease in ROP.

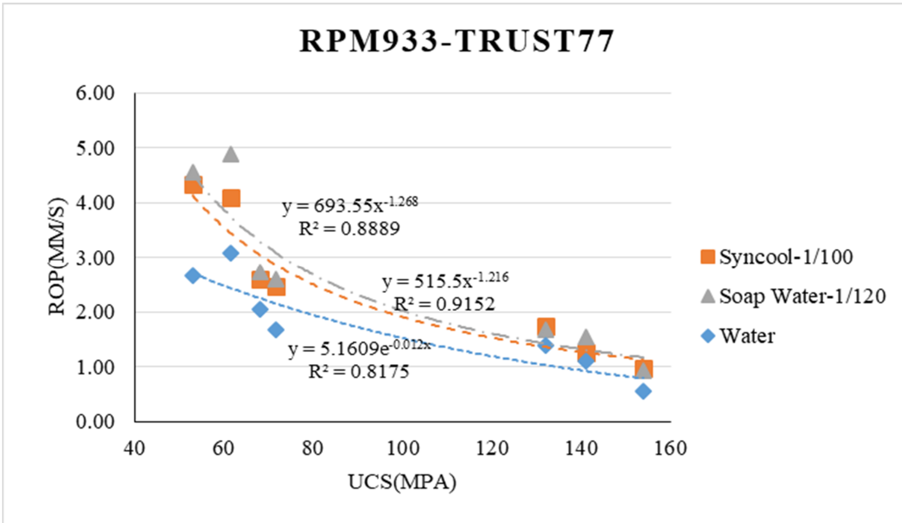


Figure 7. Relationship between UCS and ROP in the presence of FW, FS_1, FSW_2.

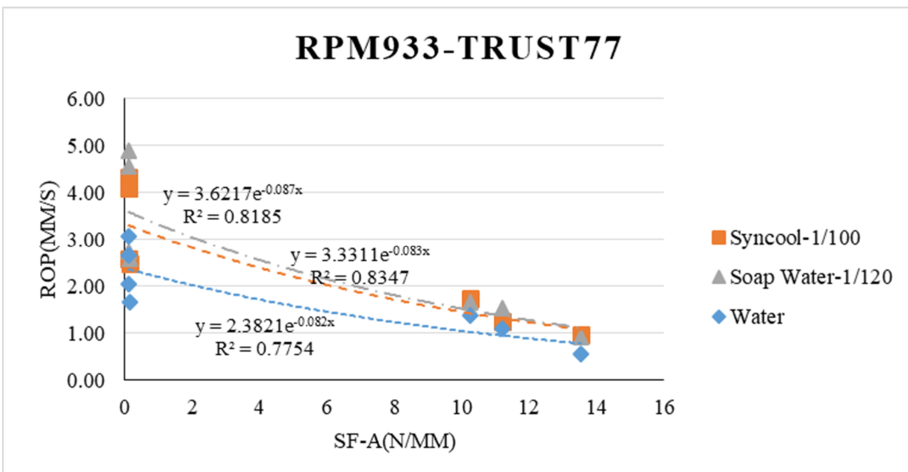


Figure 8. Relationship between SF-a and ROP in the presence of FW, FS_1, FSW_2.

As the diagram in Figure 8 shows, there is a strong exponential relationship between the SF-a of the drilled rock and ROP. This relationship follows an exponential function with a correlation coefficient of $R^2 = 0.78$ in the presence of FW, an exponential function with a correlation coefficient of $R^2 = 0.83$ in the presence of FS_1, and an exponential function with a correlation coefficient of $R^2 = 0.82$ in the presence of FSW_2 as the coolant/lubricant fluid. The general trend of this relationship suggests that, as expected, a higher SF-a leads to a decrease in ROP.

As the diagram in Figure 9 shows, there is a strong power/logarithmic relationship between MH of the drilled rock and ROP. This relationship follows a Logarithmic function with a correlation coefficient of $R^2 = 0.82$ in the presence of FW, a power function with a correlation coefficient of $R^2 = 0.88$ in the presence of FS_1, and a power function with a correlation coefficient of $R^2 = 0.86$ in the presence of FSW_2 as the coolant/lubricant fluid. The general trend of this relationship suggests that, as expected, a higher MH leads to a decrease in ROP.

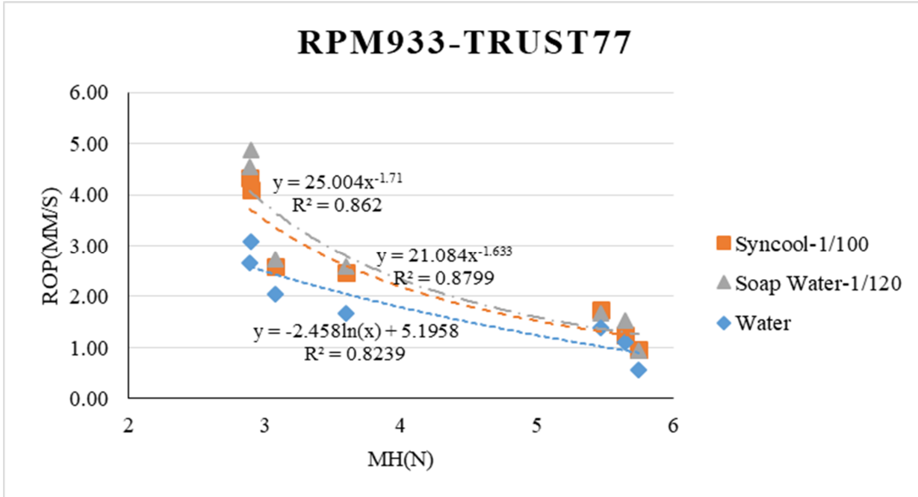


Figure 9. Relationship between MH and ROP in the presence of FW, FS_1, FSW_2.

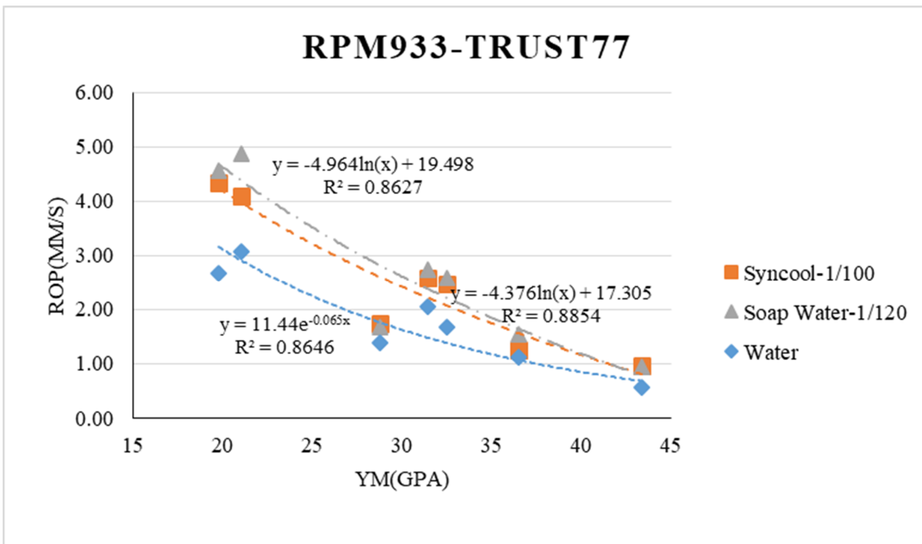


Figure 10. Relationship between YM and ROP in the presence of FW, FS_1, FSW_2.

As the diagram in Figure 10 shows, there is a strong exponential/logarithmic relationship between YM of the drilled rock and ROP. This relationship follows an exponential function with a correlation coefficient of $R^2 = 0.86$ in the presence of FW, a logarithmic function with a correlation coefficient of $R^2 = 0.89$ in the presence of FS_1, and a logarithmic function with a correlation coefficient of $R^2 = 0.86$ in the presence of FSW_2 as the coolant/lubricant fluid. The general trend of this relationship suggests that, as expected, a higher YM leads to a decrease in ROP.

Next, the same method was used in order to analyze the relationship between the physical parameters (i.e. Vis, PH, and EC) of FW, FS_1, and FSW_2 and ROP in granite, marble, and travertine under constant operating conditions of 77 Kg thrust and 933 rpm rotation speed using linear, power, exponential, and logarithmic functions, and determine which function gives the highest correlation coefficient for this relationship.

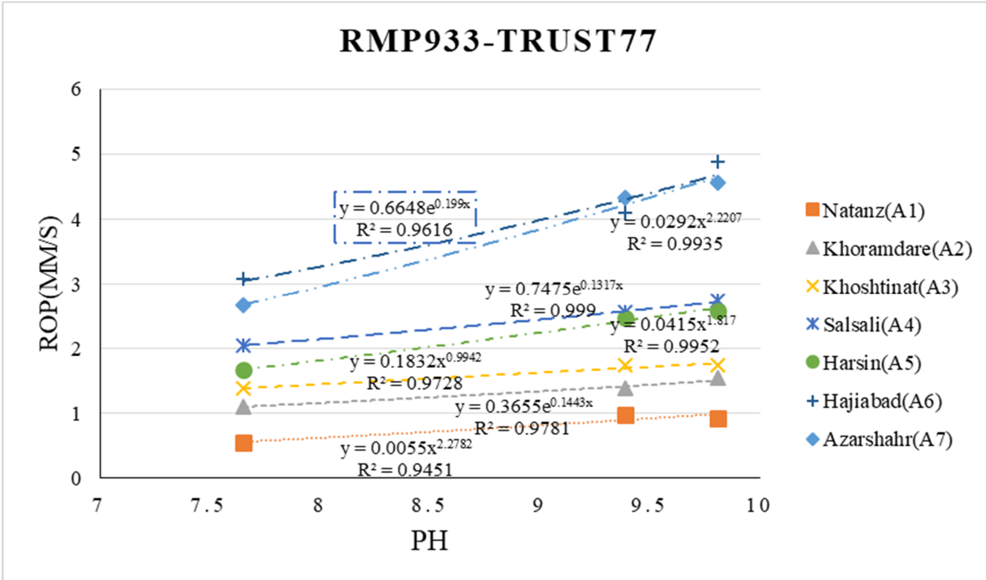


Figure 11. Relationship between pH of fluids and ROP in the tested rock specimens.

As shown in Figure 11, there is a strong exponential/power relationship between the pH of fluids and ROP. The general trend of this relationship suggests that, under almost all conditions, as the pH of the fluid increases, so does ROP. This relationship can be expressed by the following equations:

$$ROP_{A1} = 0.0055PH^{2.2782} \quad R2 = 0.94 \tag{3}$$

$$ROP_{A2} = 0.3655e^{0.1443PH} \quad R2 = 0.98 \tag{4}$$

$$ROP_{A3} = 0.1832PH^{0.9942} \quad R2 = 0.97 \tag{5}$$

$$ROP_{A4} = 0.7475e^{0.1317PH} \quad R2 = 0.99 \tag{6}$$

$$ROP_{A5} = 0.0415PH^{1.817} \quad R2 = 0.99 \tag{7}$$

$$ROP_{A6} = 0.6648e^{0.199PH} \quad R2 = 0.96 \tag{8}$$

$$ROP_{A7} = 0.0292PH^{2.2207} \quad R2 = 0.99 \tag{9}$$

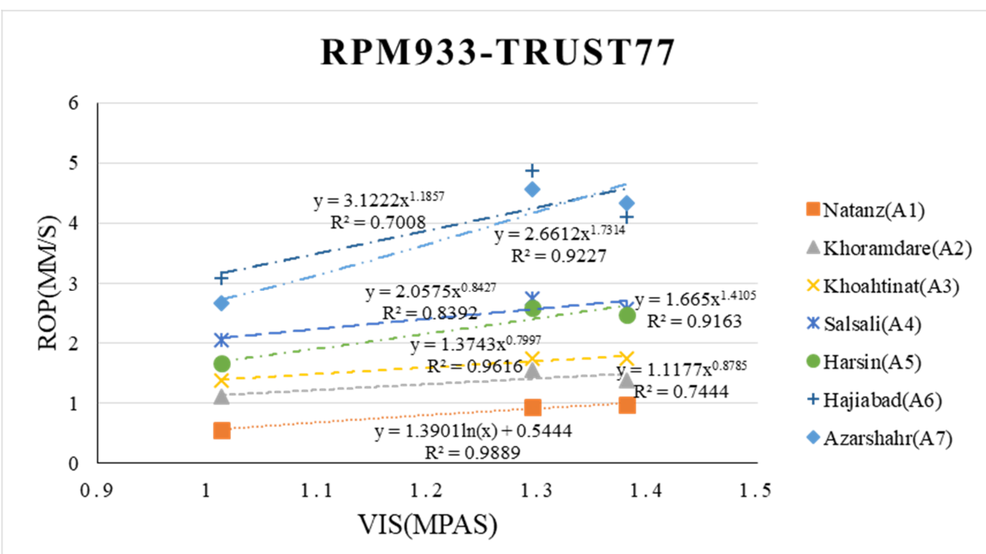


Figure 12. Relationship between the Vis of fluids and ROP in the tested rock specimens.

As shown in Figure 12, there is a strong logarithmic/power relationship between the Vis of fluids and ROP. The general trend of this relationship suggests that, under almost all conditions, as the Vis of the fluid increases, so does ROP. This relationship can be expressed by the following equations:

$$ROP_{A1} = 1.3901\ln(Vis) + 0.5444 \quad R^2 = 0.98 \tag{10}$$

$$ROP_{A2} = 1.1117 Vis^{0.8785} \quad R^2 = 0.74 \tag{11}$$

$$ROP_{A3} = 1.3743 Vis^{0.7997} \quad R^2 = 0.96 \tag{12}$$

$$ROP_{A4} = 2.0575 Vis^{0.8427} \quad R^2 = 0.83 \tag{13}$$

$$ROP_{A5} = 1.665 Vis^{1.4105} \quad R2 = 0.91 \tag{14}$$

$$ROP_{A6} = 3.1222 Vis^{1.1857} \quad R2 = 0.70 \tag{15}$$

$$ROP_{A7} = 2.6612 Vis^{1.7314} \quad R2 = 0.92 \tag{16}$$

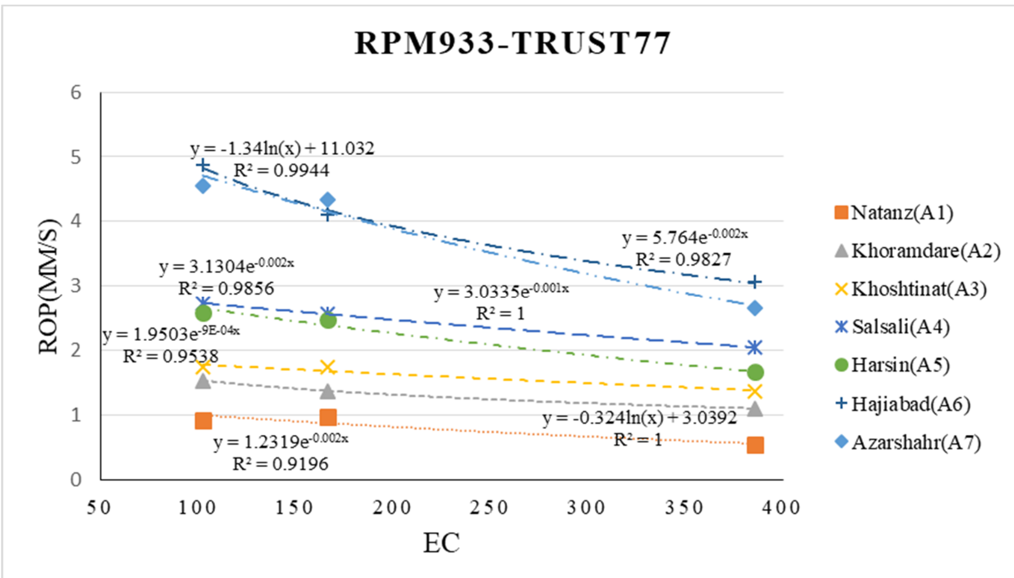


Figure 13. Relationship between EC of fluids and ROP in the tested rock specimens.

As shown in Figure 13, there is a strong exponential/logarithmic relationship between the EC of fluids and ROP. The general trend of this relationship suggests that, under almost all conditions, as the EC of the fluid decreases, ROP increases. This relationship can be expressed by the following equations:

$$ROP_{A1} = 1.2319 e^{-0.002EC} \quad R^2 = 0.92 \tag{17}$$

$$ROP_{A2} = -0.324\ln(EC) + 3.0392 \quad R^2 = 1 \tag{18}$$

$$ROP_{A3} = 1.9503 e^{-9E-04EC} \quad R^2 = 0.95 \tag{19}$$

$$ROP_{A4} = 3.0335 e^{-0.001EC} \quad R^2 = 1 \tag{20}$$

$$ROP_{A5} = 3.1304 e^{-0.002EC} \quad R^2 = 0.98 \tag{21}$$

$$ROP_{A6} = -1.34\ln(EC) + 11.032 \quad R^2 = 0.99 \tag{22}$$

$$ROP_{A7} = 5.764 e^{-0.002EC} \quad R^2 = 0.99 \tag{23}$$

Similar statistical analyses with linear, power, exponential, and logarithmic functions were performed in order to investigate the relationship between ROP and the operating parameters of the drilling rig in the presence of FW, FS_1, and FSW_2.

Figures 14-20 show the relationship between ROP and the operating parameters of the drilling rig in granite, marble, and travertine specimens.

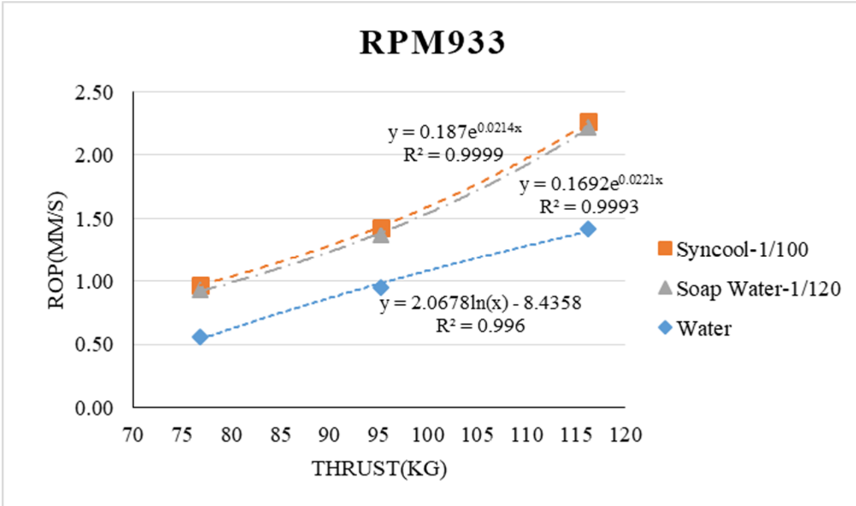


Figure 14. Relationship between ROP and thrust at a rotation speed of 933 rpm for rock specimen A_1.

Figure 14 shows the relationship between ROP and the operating parameters of the drilling rig in the drilling of rock specimen A_1 in the presence of FW, FS_1, and FSW_2. As it can be seen, at the rotation speed of 933 rpm, increasing the thrust force from 77 kg to 116 kg in the presence of FS_1 and FSW_2 leads to, respectively, 58% and 55% greater increase in ROP than doing the same in the presence of FW. This shows the good performance of these coolant/lubricant fluids in increasing ROP at higher drilling rates. The diagrams in Figures 15-20 also demonstrate this increasing trend.

Figure 15 shows the relationship between ROP and the operating parameters of the drilling rig in the drilling of rock specimen A_2 in the presence of FW, FS_1, and FSW_2. It can be seen that using FS_1 and FSW_2 instead of FW under similar conditions has increased ROP by 18% and 34%, respectively.

Figure 16 shows the relationship between ROP and the operating parameters of the drilling rig in the drilling of rock specimen A_3 in the presence of FW, FS_1, and FSW_2. It can be seen that using FS_1 and FSW_2 instead of FW under similar conditions has increased ROP by 25% and 31%, respectively.

Figure 17 shows the relationship between ROP and the operating parameters of the drilling rig in the drilling of rock specimen A_4 in the presence of FW, FS_1, and FSW_2. It can be seen that using FS_1 and FSW_2 instead of FW under similar conditions has increased ROP by 27% and 36%, respectively.

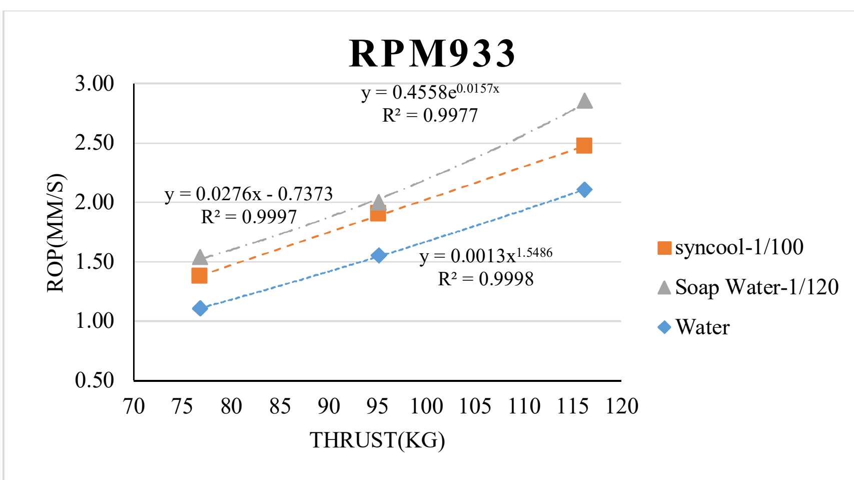


Figure 15. Relationship between ROP and thrust at a rotation speed of 933 rpm for rock specimen A2.

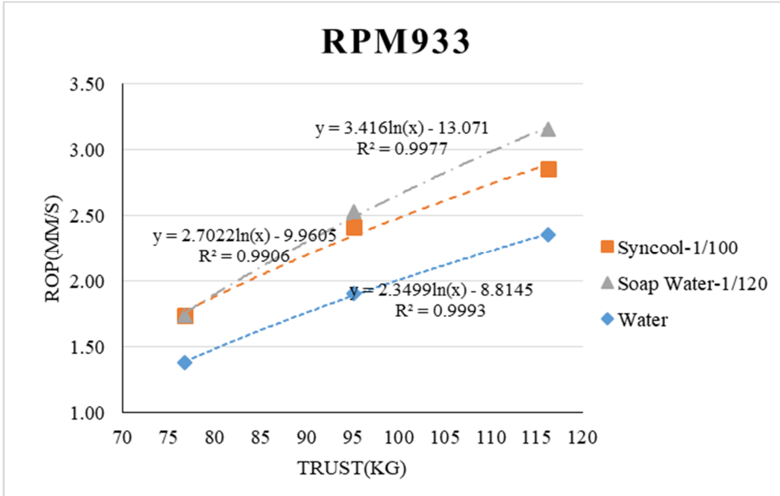


Figure 16. Relationship between ROP and thrust at a rotation speed of 933 rpm for rock specimen A_3.

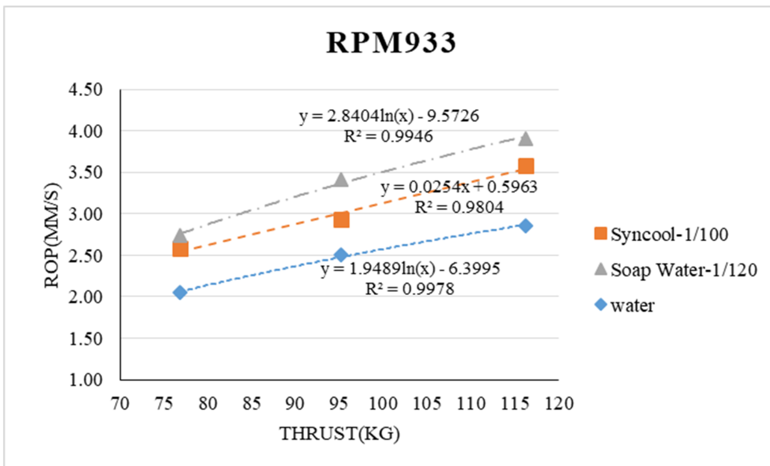


Figure 17. Relationship between ROP and thrust at a rotation speed of 933 rpm for rock specimen A_4.

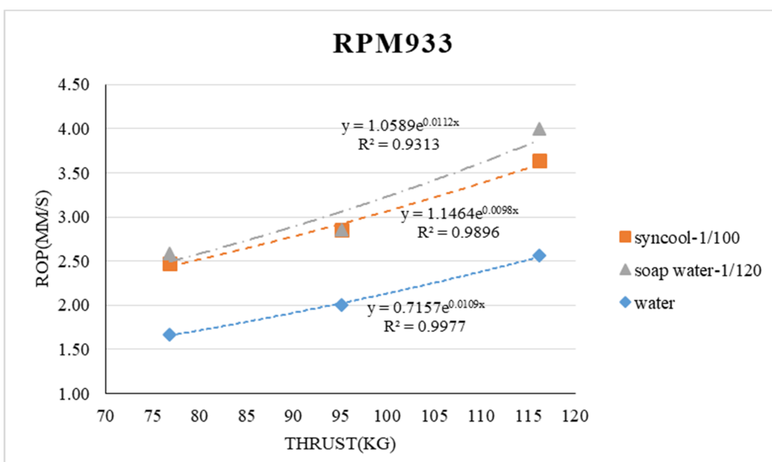


Figure 18. Relationship between ROP and thrust at a rotation speed of 933 rpm for rock specimen A_5.

Figure 18 shows the relationship between ROP and the operating parameters of the drilling rig in the drilling of rock specimen A_5 in the presence of FW, FS_1, and FSW_2. It can be seen that using FS_1 and FSW_2 instead of FW under similar conditions has increased ROP by 44% and 52%, respectively.

Figure 19 shows the relationship between ROP and the operating parameters of the drilling rig in the drilling of rock specimen A_6 in the presence of FW, FS_1, and FSW_2. It can be seen that using FS_1 and FSW_2 instead of FW under similar conditions has increased ROP by 30% and 47%, respectively.

Figure 20 shows the relationship between ROP and the operating parameters of the drilling rig in the drilling of rock specimen A_7 in the presence of FW, FS_1, and FSW_2. It can be seen that using FS_1 and FSW_2 instead of FW under similar conditions has increased ROP by 45% and 53%, respectively.

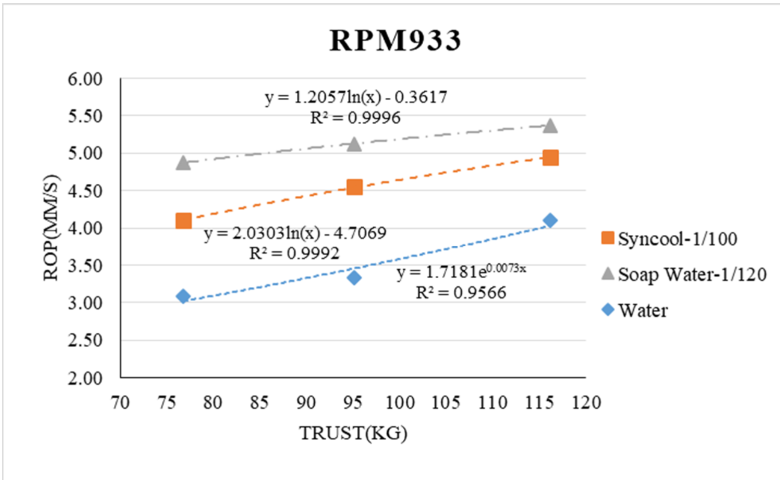


Figure 19. Relationship between ROP and thrust at a rotation speed of 933 rpm for rock specimen A_6.

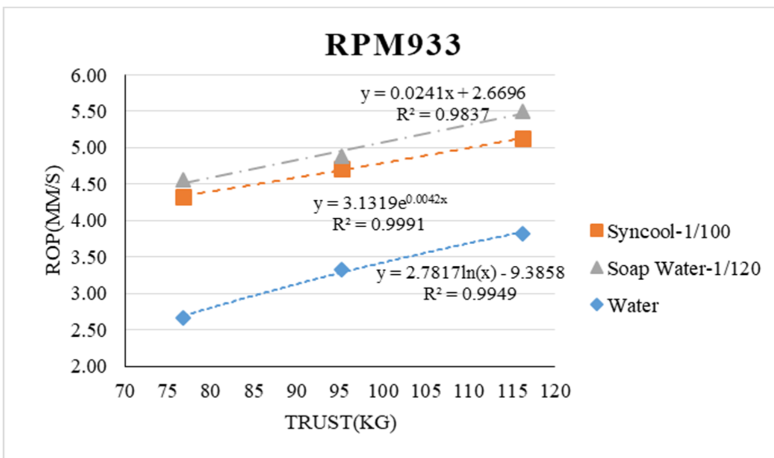


Figure 20. Relationship between ROP and thrust at a rotation speed of 933 rpm for the rock specimen A_6.

5. Discussions

Our investigation of the relationship between ROP and the mechanical properties of the rock samples showed that using FS_1 and FSW_2 instead of FW under similar conditions in terms of mechanical properties led to on average 31% and 37% increased ROP in granite, 36% and 43% increased ROP in marble, and 47% and 61% increased ROP in travertine, respectively. Therefore, all cooling/lubricating fluids offered an increased ROP compared to the normal drilling conditions, with FSW_2 outperforming FS_1 in this respect. These results demonstrate a good performance of FSW_2 as a coolant/lubricant in increasing ROP. Also our investigation of the relationship between ROP and the operating parameters showed that at a constant rotation speed (933 rpm), ROP increased with increasing thrust force. Again, the greatest ROP improvement was observed when FSW_2 was used as the coolant/lubricant, which showed its good performance in increasing ROP. This effect of FSW_2 on ROP can be attributed to its impact on the process forces (tangential and vertical forces applied to the bit), cuttings removal, and thermal stresses at the bit-rock interface, which tend to intensify with the continuation of the drilling process. In addition to increasing the forces and stresses of the process, this intensification leads to the formation and growth of the lateral and radial cracks below the bit-rock interface, which ultimately results in the formation of secondary cuttings. In other words, as the bit penetration depth increases, the formation of secondary cuttings also intensifies even to the point that they constitute a majority of cuttings in the drill hole. Thus ROP decreases if the volume of cuttings removed remains constant. This also has other effects such as increased wear of the drill bit and vibration of the rig, which ultimately increases the costs arising from the repair and maintenance and bit replacement. The best way to avoid this problem is to reduce the process forces and thermal stresses in the drill hole, which can be done using an appropriate cooling/lubricating fluid. Our results suggest that using either FS_1 or FSW_2 as the cooling/lubricating fluid can significantly reduce the process forces and thermal stresses by reducing the process friction coefficient and facilitating the timely removal of cuttings, which ultimately lead to an increased ROP.

6. Conclusions

In this work, we conducted a series of laboratory tests followed by statistical analysis in order to investigate the relationship between ROP and the mechanical properties of the drilled rock, physical properties of the fluid, and operating parameters of the drilling rig in the drilling of seven types of hard and soft rock with 6 coolant/lubricant fluids (water and five other fluids). The seven rock samples chosen for this work included three hard rocks and four soft rocks. After cutting these samples, they were transferred to a rock mechanics laboratory, where their uniaxial compressive strength, Mohs hardness, Schmiazek abrasivity factor, and Young's modulus (representing, respectively, the strength, hardness, abrasivity, and elasticity/plasticity of the rock) were measured. The pH, viscosity, and conductivity of the fluids were also measured in the laboratory. A laboratory-scale drilling rig with a diamond bit was then used in order to conduct a series of drilling tests under different operating conditions. The resulting laboratory data was then used to conduct several univariate linear regression statistical analyses. The results of these analyses showed that ROP decreased with increase in the strength, hardness, and abrasivity of the drilled rock but the slope of these changes differed depending on the cooling/lubricating fluid used. It was also found that using FS_1 and FSW_2 instead of FW under similar conditions in terms of the mechanical properties of the rock led to on average 31% and 37% increased ROP in granite, 36% and 43% increased ROP in marble, and 47% and 61% increased ROP in travertine, respectively. The results obtained also showed that at a constant rotation speed, ROP generally increased with thrust force but this increase was greater if FS_1 or FSW_2 was used rather than FW as the cooling/lubricating fluid. In general, using any of the cooling/lubricating fluids instead of pure water led to an improvement in ROP, with the greatest ROP improvement achieved with FSW_2. These results demonstrate the good performance of the tested cooling/lubricating fluids in increasing ROP.

References

[1]. Izquierdo, L.E. and Chiang, L.E. (2004). A methodology for estimation of the specific rock energy index using corrected down-the-hole drill monitoring data. Mining Technology. 113 (4): p. 225-236.

[2]. Bilgesu, H., Tetrick, L., Altmis, U., Mohaghegh, S. and Ameri, S. (1997). A new approach for the prediction of rate of penetration (ROP) values. in SPE Eastern Regional Meeting. Society of Petroleum Engineers.

[3]. Hoseinie, S., Aghababaei, H. and Pourrahimian, Y. (2008). Development of a new classification system for assessing of rock mass drillability index (RDi). International Journal of Rock Mechanics and Mining Sciences. 45 (1): p. 1-10.

[4]. Zhao, X.H., Gao, F., Li, Y.F. and Li, W. (2011). The research on the effect of drilling fluids additives on Rate of Penetration (ROP). in Advanced Materials Research, Trans Tech Publ, 2064-2071.

[5]. Long, W. (1996) The lubricating mechanisms of lubricating drilling fluids on synthetic diamond bit. Journal of Central South University of Technology. 3 (1): p. 85-87.

[6]. Westwood, A., MacMillan, N. and Kalyoncu, R. (1973). Chemomechanical effects in hard rock drilling.

[7]. Rehbinder, P., Schreiner, L. and Zhigach, K. (1944). Hardness reducers in drilling. Academy of Science, Moscow. 194 (4).

[8]. Dauncey, G. (1960). De Beers Diamond Research Laboratory. Johannesburg, South Africa, Paper.

[9]. Hammond, M. and Ravitz, S. (1963). Influence of environment on brittle fracture of silica. Journal of the American Ceramic Society. 46 (7): p. 329-332.

[10]. Selim, A., Schultz, C. and Strebig, K. (1969). The Effect of Additives on Impregnated Diamond Bit Performance. Society of Petroleum Engineers Journal. 9 (04): p. 425-433.

[11]. Cooper, G. and Berlie, J. (1976). On the influence of the flushing fluid during diamond drilling. Journal of Materials Science. 11 (9): p. 1771-1775.

[12]. Mills, J. and Westwood, A. (1978). Influence of chemomechanically active fluids on diamond wear during hard rock drilling. Journal of Materials Science. 13 (12): p. 2712-2716.

[13]. El-Shall, H., Gupta, S., Haecker, R. and Somasundaran, P. (2000). Effect of additives on drilling in hard rock. Mining Engineering. 52 (1): p. 48-52.

[14]. Rao, K., Bhatnagar, A. and Misra, B. (2002). Laboratory investigations on rotary diamond drilling. Geotechnical & Geological Engineering, 20(1): p. 1-16.

[15]. Messaoud, L. (2009). Influence of fluids on the essential parameters of rotary percussive drilling. Laboratoire d'Environnement (Tébessa), 14: p. 1-8.

[16]. Bhatnagar, A., Khandelwal, M. and Rao, K.U.M. (2010). Enhancing diamond drilling performance by the addition of non-ionic polymer to the flushing media. Mining Science and Technology (China). 20 (3): p. 400-405.

[17]. Bhatnagar, A., Khandelwal, M. and Rao, K. (2011). Laboratory investigations for the role of flushing media in diamond drilling of marble. Rock mechanics and rock engineering. 44 (3): p. 349-356.

[18]. Bhatnagar, A. and Khandelwal, M. (2012). An intelligent approach to evaluate drilling performance. Neural Computing and Applications. 21 (4): p. 763-770.

[19]. Li, W., Zhao, X., Li, Y., Ji, Y., Peng, H., Liu, L. and Yang, Q. (2015). Laboratory investigations on the effects of surfactants on rate of penetration in rotary diamond drilling. Journal of Petroleum Science and Engineering, 134: p. 114-122.

[20]. Rawal, R., Karmakar, N. and Sharma, S. (2016). Effect of fluid additives on rock drilling. in Recent Advances in Rock Engineering, Atlantis Press, 2352-5401.

[21]. Taheri, A., Qao, Q. and Chanda, E. (2016). Drilling penetration rate estimation using rock drillability characterization index. Journal of The Institution of Engineers (India): Series D. 97 (2): p. 159-170.

[22]. Wang, C. and Li, S. (2018). Evaluation of Rock Abrasiveness Based on PDC Compact Wear Model. Recent Patents on Engineering. 12 (2): p. 153-163.

[23]. Shad, H.I.A., Sereshki, F., Ataei, M. and Karamoozian, M. (2018). Prediction of rotary drilling penetration rate in iron ore oxides using rock engineering system. International Journal of Mining Science and Technology. 28 (3): p. 407-413.

[24]. Xiao, Y., Hurich, C. and Butt, S.D. (2018). Assessment of rock-bit interaction and drilling performance using elastic waves propagated by the drilling system. International Journal of Rock Mechanics and Mining Sciences, 105: p. 11-21.

[25]. Shankar, V.K., Kunar, B.M., Murthy, C.S. and Ramesh, M. (2020). Measurement of bit-rock interface temperature and wear rate of the tungsten carbide drill bit during rotary drilling. Friction. 8 (6): p. 1073-1082.

[26]. Piri, M., Hashemolhosseini, H., Mikaeil, R., Ataei, M. and Baghbanan, A. (2020). Investigation of wear resistance of drill bits with WC, Diamond-DLC, and TiAlSi coatings with respect to mechanical properties of rock. International Journal of Refractory Metals and Hard Materials, 87: p. 105113.

[27]. Liao, X., Khandelwal, M., Yang, H., Koopialipoor, M. and Murlidhar, B.R. (2020). Effects of a proper feature selection on prediction and optimization of drilling rate using intelligent techniques. Engineering with Computers, 36(2): p. 499-510.

[28]. Shangxin, F., Yujie, W., Guolai, Z., Yufei, Z., Shanyong, W., Ruilang, C. and Enshang, X. (2020). Estimation of optimal drilling efficiency and rock strength by using controllable drilling parameters in rotary non-percussive drilling. Journal of Petroleum Science and Engineering, 193: p. 107376.

[29]. Kolapo, P. (2021). Investigating the Effects of Mechanical Properties of Rocks on Specific Energy and Penetration Rate of Borehole Drilling. Geotechnical and Geological Engineering. 39 (2): p. 1715-1726.

[30]. Lawal, A.I., Kwon, S. and Onifade, M. (2021). Prediction of rock penetration rate using a novel Antlion optimized ANN and statistical modelling. Journal of African Earth Sciences, p. 104287.

[31]. Piri, M., Mikaeil, R., Hashemolhosseini, H., Baghbanan, A. and Ataei, M. (2021). Study of the effect of drill bits hardness, drilling machine operating parameters and rock mechanical parameters on noise level in hard rock drilling process. Measurement, 167: p. 108447.

[32]. Brown, E.T. (1981). Rock characterization testing and monitoring: ISRM suggested methods. Oxford, Pergamon. 171-183.

[33]. Yavuz, H., Ozkahraman, T. and Demirdag, S. (2011). Polishing experiments on surface quality of building stone tiles. Construction and Building Materials. 25 (4): p. 1707-1711.

[34]. Ersoy, A. and Waller, M. (1995). Textural characterisation of rocks. Engineering geology, 39(3-4): p. 123-136.

مطالعه تاثیر سیالات خنک کننده و روان کار، پارامترهای عملیاتی و خصوصیات مکانیکی سنگ بر روی نرخ نفوذ در عملیات حفاری سنگ

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چکیده:

در اکثر فرایندهای حفاری سنگ دلیل عمده کاهش میزان نرخ نفوذ حفاری وجود تراشه‌های حاصل از عملیات حفاری و تنش‌های حرارتی ناشی از اصطکاک میان سرمته و سنگ می‌باشد، که با افزایش سختی، سایندگی و پارامترهای مقاومتی سنگ این موضوع تشدید می‌شود. به منظور افزایش توان تراشه برداری سرمته الماس، در کنار کاهش نیروهای فرایند که در اثر اندرکنش مکانیکی بین سرمته و سنگ بوجود می‌آید، می‌بایست میزان تنش‌های حرارتی تولید شده را به حداقل ممکن رساند تا علاوه بر افزایش میزان نرخ نفوذ، عمر ابزار را نیز بهبود بخشید. از دیدگاه فنی و اقتصادی هرگونه بهبود در فرآیند حفاری اهمیت فوق العاده‌ای دارد و یکی از مهم ترین راه کارها برای دست یابی به این هدف استفاده از یک سیال خنک کننده و روان کار مناسب در محیط حفاری می‌باشد تا علاوه بر افزایش میزان نرخ نفوذ و کاهش دمای محیط حفاری، محیطی پاک و عاری از خرده سنگ‌های حاصل از حفاری ایجاد کرد. در این تحقیق به بررسی و مقایسه افزایش میزان نرخ نفوذ در شرایط استفاده از ۶ نمونه سیال خنک کننده و روان کار در طی فرایند حفاری در ۷ نمونه سنگ شامل سنگ های سخت و نرم پرداخته شده است. آزمایش های حفاری با استفاده از یک دستگاه حفاری در مقیاس آزمایشگاهی بر روی نمونه‌های مکعبی در چندین سرعت‌های چرخش و بارهای پشت مته متفاوت انجام شد. به منظور بررسی ارتباط میان میزان نرخ نفوذ حفاری با مشخصات مکانیکی سنگ، مشخصات فیزیکی سیال و پارامترهای عملیاتی دستگاه، مطالعات آماری رگرسیون تک متغیره خطی انجام شد. نتایج حاصل از بررسی مطالعات آماری تک متغیره خطی نشان داد که تحت شرایط مختلف حفاری در نمونه سنگ‌های مورد آزمایش، میزان نرخ نفوذ در شرایط استفاده از سیال سینکول با غلظت ۱به ۱۰۰ و سیال آب صابون با غلضت ۱به ۱۲۰ در مقایسه با سیال آب به ترتیب در شرایط یکسان، از نظر پارامترهای مکانیکی سنگ، در نمونه سنگ‌های گرانیتی به طور میانگین تقریبا ٪۳۱ و ٪۳۷ درصد و در نمونه سنگ‌های مرمریت تقریبا ٪۳۶ و ٪۴۳ و در نمونه سنگ‌های تراورتن تقریبا ٪۴۷ و ٪۶۱ افزایش پیدا کرده است. این تغییرات نشان دهنده عملکرد خوب سیال خنک کننده و روان کار در افزایش میزان نرخ نفوذ حفاری می‌باشد.

کلمات کلیدی: حفاری، نرخ نفوذ، سیال خنک کننده و روان کار، مطالعات آماری، تک متغیره خطی.