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Studying Effects of Cooling/Lubricating Fluids, Machining Parameters, and Rock Mechanical Properties on Specific Energy in Rock Drilling Process

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Abstract

Specific energy is a key indicator of drilling performance to consider in the feasibility and economic analyses of drilling projects. Any improvement in the specific energy of a drilling operation may reflect an improvement in the overall efficiency of drilling operations. This improvement can be achieved by delivering a suitable cooling lubricant into the drilling environment. The present study examines the mechanical characteristics of the drilled rock, the physical qualities of the cooling lubricant employed, and the drilling rig operational parameters related to the drilling-specific energy (DSE). To this end, seven rock samples (granite, marble, and travertine) were drilled using water and five other fluids as the cooling lubricants. A total of 492 drilling experiments were conducted with a custom-designed and built laboratory-scale drilling rig on cuboid rock specimens. The univariate linear regression analysis of experimental results revealed a significant drop in DSE after using cooling lubricants instead of conventional cooling fluid (i.e. water). Under constant 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 water led to 34% and 43% DSE reductions in the granite samples, 48% and 54% in the marble samples, and 41% and 50% in the travertine samples, respectively. These variations in specific energy suggest that the drilling efficiency and performance can be augmented using properly selected cooling lubricants.

1. Introduction

Rock drilling is an expensive operation [1] with an essential role in several industries including construction, mining, and oil and water well drilling [2]. Therefore, drilling performance is of significant importance for the feasibility and economics of such projects [3]. Various reports on the amount of energy consumed in drilling processes indicate that they are energy-intensive, although the exact amount is a function of the rock's hardness and resistance parameters [4]. In any case, drilling and excavation processes should always be optimized to maximize performance and minimize energy consumption. Specific energy consumption, as a criterion proportional to the amount of rock removed per unit volume, is a good indicator of the efficiency of drilling operations [5]. Research has shown that drilling specific energy (DSE) is a better criterion than the other available indicators for assessing the performance of rock drilling operations [5-7]. In addition, DSE serves as a highly practical measure of both drilling efficiency and rock properties [8, 9]. In diamond drilling operations, any performance improvement can significantly impact the economy of operations by reducing energy consumption, prolonging bit lifetime, reducing bit wear rate, increasing drilling speed, and generally reducing drilling costs. One way to achieve such an improvement is to use appropriate cooling lubricants in the drilling process [10]. Indeed, various cooling lubricants can

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be used in diamond drilling operations [11]. Water is the fluid most commonly used for cooling in these operations. However, adding additives to water to improve its cooling and lubricating properties can result in better cooling of the drilling bit, reduced process forces, reduced specific energy consumption, tool wear rate, less concentration of thermal stresses at the bit-rock interface, better and faster removal of cuttings from the drill hole, and better lubrication of the bit-rock interface. These additives result in less friction and energy loss, prolonged bit life, less corrosion in both the rock and the tool, improved stability, and reduced vibration. Hence, using cooling lubricants lowers the costs and improve the diamond drilling operations' performance [12-15]. Researchers have examined some strategies to increase the effectiveness of drilling operations over the past 50 years. One of these techniques is using chemical additives to modify the rocks' surface characteristics. To this end, the amount of energy used in drilling operations can be reduced considerably by increasing drilling speed through adding these compounds to the drilling fluid [16]. In this respect, Salim *et al*. (1969) investigated the effects of organic additives used in drilling fluids on the effectiveness of diamond drilling operations. The authors indicated that adding these additives to the drilling fluid increases the rate of penetration (ROP) and decreases the coefficient of friction, torque, and wear rate. The cited study also reported that adding these additives to the fluid reduces the energy consumed per unit volume of rock removed, thereby significantly lowering the drilling costs [17]. Clark (1987) investigated the factors affecting rock disintegration. According to these researchers, using cooling lubricants increases drilling speed and decreases energy consumption by reducing thermal stresses and friction at the bit-rock interface and facilitating the removal of cuttings from the drilling environment [18]. Pahlman *et al*. (1989) assessed the effect of various water additives on drilling three rock samples. According to their results, polyethylene oxide (PEO), as one of these additives used for this purpose, improved ROP and bit lifetime more effectively [19]. Miller and Ball (1990) studied the effect of drilling rig operational characteristics on drilling efficiency. The results demonstrated that increasing the thrust force up to a certain amount lowers specific energy, but using larger forces failed to exert the same effect. In other words, there was an optimal thrust force in which the specific energy was minimized with ROP at an optimal level. They also reported that ROP and torque both increased linearly with increasing the thrust force [20]. John and Rao (1997) examined the effect of operating factors of drilling rig and cooling fluid on diamond drilling performance. The study showed that cooling fluid usage reduced the bit wear rate and improved the drilling performance [21]. In another study, Staroselsky and Kim (1997) investigated the impact of using surfactant additives within water on the drilling rate. These authors reported that using the additive-containing water instead of plain water doubled the size of cracks made in rock and the size of cuttings removed by the bit [22]. Rao *et al*. (2002) conducted extensive laboratory tests on a variety of rocks to determine the effect of additives on the efficiency of rotary diamond drilling operations. According to their results, drilling with fluid containing additives required less specific energy than drilling with water [23]. Studying the impact of specific energy of drilling on ROP, Kahraman *et al*. (2003) showed that specific energy and ROP are inversely correlated [24]. Dupriest (2005) asserted that specific energy is a significant factor in improving drilling performance because accurate and timely monitoring of specific energy could facilitate the optimization of operating parameters and ROP, thereby enhancing efficiency and declining the drilling costs [25, 26]. Armenta (2008) studied the effect of specific energy on drilling efficiency. The results showed that drilling efficiency tended to be low when ROP was low and specific energy was high; meanwhile, it was high when ROP was high and specific energy was low [27]. Messaoud (2009) conducted a series of laboratory experiments to determine the effect of cooling/lubricating fluids on drilling performance. The findings revealed that using cooling lubricants as opposed to plain water increased ROP and decreased specific energy at a constant rotation speed of drill bit [1]. Bhatnagar *et al*. (2010) explored the impact of adding non-ionic polymers to water on ROP and torque in diamond drilling. The results showed that torque increased linearly with increasing thrust force at all drill rotation rates. Also it was found that using PEO-containing fluid instead of plain water resulted in a slight decrease in torque [28]. Bhatnagar *et al.* (2011) conducted some laboratory studies to determine the effect of PEO on marble diamond drilling. These researchers examined the impact of coolant on ROP, torque, and specific energy for various thrust forces and rotation speeds. The results showed that applying the fluid containing the additive enhanced ROP, while it lowered torque and specific energy [12]. Laboratory studies conducted in the laboratory by Yasar *et al*. (2011)

on the effect of operating parameters on drilling performance revealed that specific energy depends on both operating parameters (i.e. thrust force and torque) and rock properties. According to this study, specific energy is inversely related to uniaxial compressive strength (UCS), thrust force, torque, and ROP [29]. Li and Itakura (2012) studied the correlation between drilling performance and strength properties of rock. The results showed that specific energy increases with increasing UCS, and decreases with increasing torque and ROP [30]. Yaralı *et al*. (2014) investigated the relationship between drilling rate, mechanical properties of rock, bit wear rate, and specific energy for 32 rock samples. In this study, simple linear regression analysis revealed a direct relationship between rock strength, wear rate, and drilling rate, all affecting the specific energy [31]. Lee *et al*. (2015) investigated the impact of using surfactants in rotary diamond drilling on ROP. The results indicated that using the fluid containing the surfactant increased ROP proportional to the additive's concentration [32]. Abbott (2015) found that specific energy can be used to optimize drilling performance, shorten the drilling time, and lower the drilling costs [33]. Ghosh *et al*. (2015) studied the impact of specific energy on rotary drilling performance. In this research work, specific energy was considered an indicator of the mechanical efficiency of the rock degradation process. The findings revealed that specific energy is a function of rock characteristics and drilling rig operating factors. Also it was inversely correlated with torque and ROP and a directly correlated with rock hardness [34]. Rawal *et al*. (2016) examined the impact of substituting three polymeric additives for plain water in sandstone drilling on ROP. The results showed that applying an exact concentration of such additives improved drilling performance [35]. Mohammadi Behboud *et al*. (2016) investigated the relationship between specific drilling energy and geomechanical parameters of rocks. According to these authors, UCS is among the most influential parameters on specific drilling energy [36]. Hosseini *et al*. (2019) explored the impact of cooling and lubricating fluids on the efficiency of cutting discs when employed in the context of hard rock processing. Their results showed that using these fluids led to a noticeable reduction in electrical current consumption during the cutting process for hard rock materials [37]. Hosseini *et al*. (2020) probed the influence of coolant and lubricant fluids on maximum electrical current levels. Their findings advocate the pivotal role of these fluids in reducing electrical current consumption and enhancing the efficiency of rock-cutting operations [38]. Hosseini *et al*. (2020) applied artificial intelligence models to examine the impact of cooling and lubricant fluids on the cutting performance of dimension stones. Therefore, they concluded that these models exhibit high accuracy in predicting maximum electrical current during the cutting process of hard rocks [39]. Shankar *et al*. (2020) investigated the relationship between thermal stresses at the bit-rock interface and the bit wear rate during rotary drilling. The results of linear regression analysis revealed that the wear rate increased by increasing the temperature at the bit-rock interface [40]. Li *et al*. (2020) performed a series of laboratory experiments to investigate the impact of drilling rig operating parameters and rock properties. Next, they determined drilling efficiency based on ROP and specific energy. The regression analysis outcomes revealed a satisfactory correaltoin between specific energy and operating parameters. The researchers also developed a model with a high correlation for predicting ROP [41]. Feng *et al*. (2020) attempted to maximize the drilling efficiency by modifying controllable operating parameters. According to their results, the relationship between thrust force and specific energy was linear at low rotation speeds. However, at higher rotation speeds, increasing in thrust force initially decreased and then increased drilling operational paramters. In this study, specific energy increased linearly with increasing ROP at low rotation speeds but not at higher rotation speeds. In comparison, specific energy decreased by increasing ROP for a constant rotation speed [42]. Kolapo (2020) explored the mechanical characteristics of five different rock samples to determine the energy required to drill them. The results demonstrated that specific energy increased with increasing UCS. They also identified specific energy as one of the most crucial factors influencing drill bit performance (the higher the specific energy, the lower the performance). According to these authors, this parameter could be used to optimize ROP [43].

Al-Rubaii *et al*. (2020) proposed a method for ROP optimization based on specific energy. The results showed ROP improvements by 44% and specific energy reductions by 48%, thereby offering a 40% overall improvement in the drilling performance [44]. Yu *et al*. (2021) conducted a series of experiments to determine the relationship between rock strength, drillability index, and specific energy. Accordingly, they presented two models for estimating rock strength based on drilling parameters. The results indicated that rock strength could be predicted more accurately based on the drillability index than specific energy [45]. Khosravimanesh *et al*. (2021) investigated the impact of cooling/lubricating fluids and operational parameters, along with the mechanical characteristics of the rocks, on penetration rate in drilling operations. Concerning the rock's operational and mechanical parameters, the results indicated that the penetration rate using cooling/lubricating fluids increased significantly compared to water fluid under the same conditions [46]. Khosravimanesh *et al*. (2021) conducted some laboratory tests to determine the effect of cooling/lubricating fluids on the drilling penetration rate in both soft and hard rocks. They employed multivariate and non-linear regression analyses. The statistical results of selective models showed that the confidence level and correlation coefficient were over 90% value. Therefore, it was possible to accurately assess the penetration rate in drilling operations using the mechanical properties of rocks, fluid characteristics, and drilling rig specifications [47]. Hosseini *et al*. (2022) explored the correlation between the texture coefficient and electrical current consumption of cutting machinery when employing various lubricants and cooling fluids. The results showed no significant relationship between the texture coefficient and the electrical current consumption of the cutting machinery when processing hard rocks. Furthermore, the results showed the relatively minimal influence of lubricant type on the cutting machinery's performance [48].

Mekaeil *et al*. (2022) examined the impact of cooling and lubricant fluids on the amperage draw during disc-cutting performance on hard rocks. The models developed for this purpose demonstrated the feasibility of accurately predicting the amperage draw of disc-cutting machines based on the characteristics of cooling and lubricant fluids [49]. Shaffiee Haghshenas *et al*. (2022) conducted statistical studies to assess rock-cutting performance. The results indicated that energy consumption, considering operational parameters and mechanical properties of rocks, was a significant factor in examining rock-cutting performance [50]. Taiwo *et al*. (2023) conducted laboratory research on the influence of rock properties on improving the performance and efficiency of drilling bits. Their proposed method can be used to improve drilling operations in real-world scenarios [51]. In another study, Rezaei and Nyazyan (2023) evaluated the effect of rock properties on drilling rates in marble mining. According to this study, drilling efficiency can be enhanced by a comprehensive understanding of drilling conditions and rock properties [52].

In the previous lines, we conducted a literature review on specific energy and the effect of cooling lubricants on drilling performance. The results indicate a lack of a comprehensive investigation into the effect of the physical qualities of the cooling lubricant or the physical-mechanical characteristics of the rock being drilled on drilling performance. Besides, most studies in this field have focused on the effect of drilling rig operating parameters on drilling performance in the presence of specific energy. In this respect, research has reported specific energy as the most important predictor of drilling performance. Also minimizing the amount of energy consumed during drilling can greatly facilitate cost minimization and speed and efficiency maximization. Hence, the present study explored the interaction between the drilled rock's mechanical characteristics, the characteristics of the cooling lubricant used, and the operational characteristics of the drilling rig. To this end, the influence of four key mechanical properties of the rock (i.e. uniaxial compressive strength, Schimazek's F-abrasiveness factor, Young's modulus, and Mohs hardness) and the impact of three important fluid properties on the specific energy (i.e. pH hardness, viscosity, and conductivity) were investigated under various operational conditions. These conditions included thrust force, drill bit rotation speed, and the presence of a cooling fluid and a lubricant. Reviewing the various studies reveals the lack of an exhaustive study in this field. Therefore, the present study conducted comprehensive studies and experiments, which are considered the research strengths and innovations. Overall, it can be stated that using a coolant and lubricant reduces and eliminates the chips generated from the drilling process, reduces friction and thermal stresses resulting from the contact between the bit and the rock, and decreases the process forces resulting from the interaction between the bit and the rock. As a result, these factors can increase the penetration rate, lower the bit wear rate, and reduce energy consumption. This specific energy reduction obtained from drilling tests using cooling and lubricating fluids can be used to improve drilling operations in mines and related industries. Since rock drilling operations in mines are among the most energy-intensive industrial processes in energy consumption, using cooling and lubricating fluid to reduce energy consumption can significantly reduce drilling and mining costs and improve drilling performance.

2. Method

The present study was performed in two phases: a field phase and a laboratory phase. The first phase involved collecting rock samples and selecting cooling lubricant samples, cutting them to desired dimensions, transferring them to the rock mechanics laboratory, and preparing the cooling lubricant solutions in desired concentrations. The second phase comprised preparing the rock samples for laboratory experiments, measuring their mechanical properties, determining the physical characteristics of cooling lubricants, constructing a laboratory-scale drilling rig able to measure and record torque along with power consumption, and performing drilling tests on cubic rock samples while using different concentrations of cooling lubricants. After these tests, the results were analyzed using univariate linear regression. Figure 1 depicts the procedure followed in this investigation.

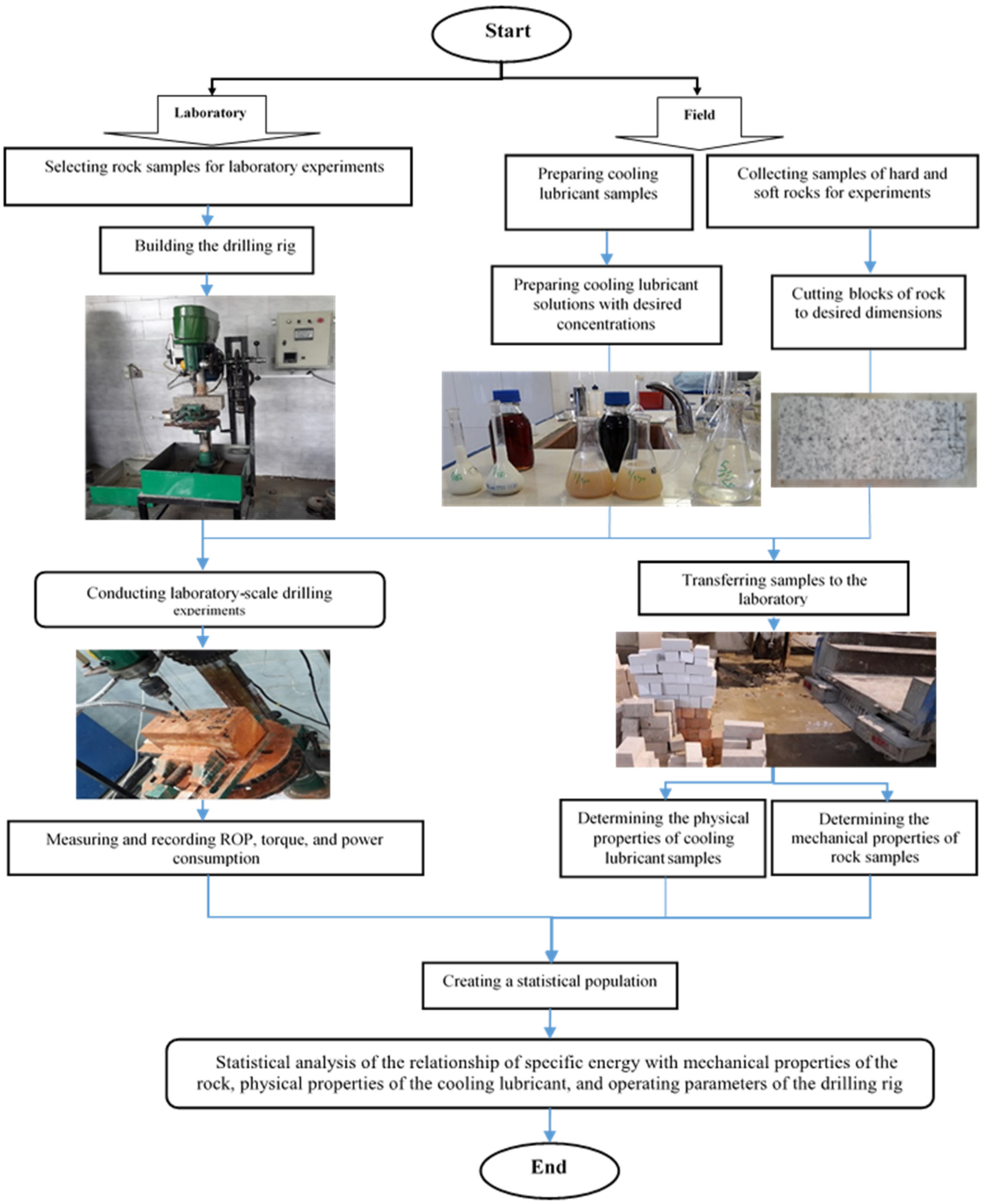

Figure 1. A flowchart of the study procedure.

3. Field and Laboratory Studies

This section describes the field and laboratory phases of the investigation into the relationship between specific energy and the mechanical properties of rock samples, the physical characteristics of cooling lubricant samples, and the operational parameters of the drilling rig.

3.1. Field phase

Selecting rock samples for research in the mining industry is very important in rock mechanics. Also the outcomes of rock mechanics experiments are highly dependent on the quality of these samples. Therefore, it is crucial to collect samples representative of the studied rock masses. The rock samples used in the experiments of the present study were seven blocks of granite, marble, and travertine collected from multiple quarries and stone-cutting factories. Table 1 shows the brand name and type of these rocks.

Table 1. Name and type of collected rock samples.

Rock sample	Type of rock	Commercial name	Name of quarry
A_1	Hard	Granite	Sefid Natanz
A_2	Hard	Granite	Khoramdare
A_3	Hard	Granite	Khoshtinat
A_4	Soft	Marble	Salsali
A_5	Soft	Marble	Harsin
A_6	Soft	Travertine	Hajiabad
A_7	Soft	Travertine	Azarshahr

The authors then created a shortlist of the best cooling lubricants available on the market based on their cooling and lubrication properties. Also after consulting with experts in the field, five options with varying concentrations were selected. The brand name and concentration of these cooling lubricants and the codes used to refer to their samples are provided in Table 2.

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

Fluid sample	Name/Brand	Abbreviation
B_1	Water	FW
B_2	Soap water with a concentration of 1/60	FSW_1
B_3	Soap water with a concentration of 1/120	FSW_2
B_4	Syncool with a concentration of 1/100	FS_1
B_5	Syncool with a concentration of 1/150	FS_2
B_6	Boron nitride powder with a concentration of 5/20	FBN
*All concentrations are provided in liters of additive dissolved in the indicated volume of water		

3.2. Laboratory phase

The laboratory studies consisted of two phases: 1) measuring the mechanical properties of collected rock samples and the physical properties of selected cooling lubricants, and 2) constructing a laboratory-scale drilling rig and using it to conduct drilling experiments on the rock samples while spraying the cooling lubricants into the drill hole.

Suitable standard techniques were used to measure the rocks' mechanical characteristics as follows:

a). Uniaxial Compressive Strength (UCS)

b). Schmiazek's F-abrasiveness factor (SF-a)

c). Young's Modulus (YM)

d). Mohs Hardness (MH)

The selected rock samples included three granite, two marble, and two travertine samples. The authors exerted caution to avoid as much as possible areas with visible discontinuities, cracking, secondary filling, and fault lines when collecting samples. The explanation is that these cases would introduce significant errors in the results. The UCS, Schmiazek's F-abrasiveness factor, Young's modulus, and Mohs hardness of the collected samples were measured through the procedures instructed by the International Society for Rock Mechanics (ISRM) [53].

The UCS test is the most prevalent laboratory test for measuring the mechanical strength of intact rock. This test is applied extensively in a variety of engineering projects. Moreover, the impact of UCS on drilling performance has been investigated by numerous researchers.

For this test, diamond core drilling equipment was used to extract five cylindrical specimens with a length-to-diameter ratio of 2.5:1 from each rock sample. The specimens' top and bottom surfaces were polished until they were completely smooth. The UCS test was performed by applying load at a constant rate of 1 MPa/s until failure and recording the maximum applied load at the failure moment. The UCS of each rock sample was determined by averaging the results obtained from its cylindrical specimens.

Schmiazek's F-abrasiveness of collected rock samples was determined using Eguation (1) [54].

$$SFa = \frac{EQC \times Gs \times BTS}{100} \tag{1}$$

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

As another indicator of the hardness of rocks and minerals, Mohs hardness is applied to determine whether they can scratch a reference object. This research determined Mohs hardness according to the percentage of constituent minerals. To this end, authors took thin sections from the typical part of the samples, determined the percentage of constituent minerals, and then estimated the average hardness of the sample as a whole using Eguation (2) [54]:

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

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

The elasticity of the samples was determined using Young's tangent modulus, which is the slope of the line tangent to the axial stress-strain curve at a location with 50% of the ultimate strength. Table 3 presents the results of these characterization tests.

Table 3. Significant mechanical characteristics of studied rocks.

Rock sample	Commercial name	Quarry name	UCS (MPa)	SF-a (N/mm)	YM (GPa)	MH (n)
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

The next step of the laboratory phase of the study was to determine the physical properties of chosen cooling lubricants at selected concentrations. The parameters measured for this purpose were pH, viscosity, and conductivity. Table 4 shows the results of the pH, viscosity, and conductivity tests for the six chosen cooling lubricants.

Table 4. Physical properties of the studied fluids.

Fluid sample	Commercial name	Concentration of the additive in the water	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	1/150	1.196	8.86	152.8
B_6	Boron nitride powder	5/20	1.155	8.17	238.9

3.3. Laboratory-scale drilling rig

To ensure that the results of drilling experiments are uniform and comparable, the authors constructed and designed a laboratory-scale drilling rig to meet the requirements of the study. Then it was used for all these tests.

This rig was designed such that the operating parameters could be modified with ease. The two main components of this rig were a drill (which performed the drilling) and a panel (which was used to control the operation and transmit instructions to the rig).

The panel, which featured a touch screen and a CPU, was responsible for managing and logging the drilling data. The thrust force applied behind the drill could be adjusted by a system of gears and chains and the weights suspended beside the rig. The drill rotation speed was adjustable and could be specified through the panel. The rig was run to drill the rock following the instructions while continuously monitoring ROP, torque, power consumption, and lubricant flow rate. The gathered data was stored in a file. The to-be-drilled rock was positioned on a circular plate that could move vertically. This plate was fitted with a clamp to hold the specimen in place. The lubricant was poured into a tank beneath the rig and then pumped to a flushing system next to a bit, where it was sprayed on the specimen. The flushing system could be positioned in any direction, and a valve placed in the fluid channel allowed the user to adjust the lubricant flow rate. The drill bit applied in the studies was a 10-mm tungsten carbide bit with a diamond blade made for drilling in granite and other hard rocks. For drilling experiments, the collected rock samples were cut into cuboids with approximate dimensions of 10 × 10 × 15 cm^3, 10 × 10 × 20 cm^3, and 10 × 10 × 30 cm^3. Drill points were selected with a minimum distance of 30 mm (more than twice the bit diameter) regarding the drill bit's 10-mm diameter. Figure 2 illustrates the drilling rig, the selected drill bit, and the specimen of rock prepared for drilling.

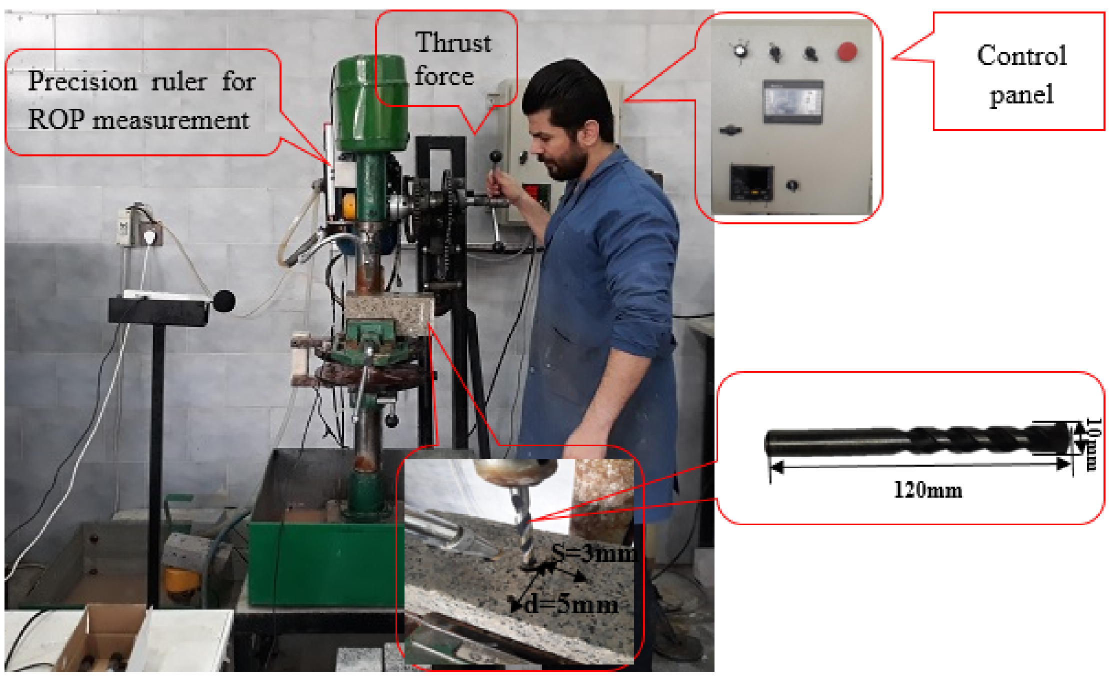

Figure 2. Drilling test tools.

3.4. Specific energy calculation

Teale (1965) was the first to establish the concept of specific energy to determine the drillability of rocks. Specific energy is the quantity of energy required to eliminate a unit volume of rock. This energy is proportional to the rate of penetration into the rock mass in an efficient drilling operation [55]. According to numerous sources, the specific energy is the most important criterion for measuring and comparing the performance of a drilling operation. In this investigation, specific energy was calculated using Eguation (3) [12]:

$$\text{Specific Energy (SE)} = (2\pi RNF_T / Pr\ A) + (F_N Pr / Pr\ A)$$
$$\text{The specific energy} = \text{(work done per minute) / (volume of rock removed)} \tag{3}$$

where FT denotes the torque force (N), R represents the operating radius of torque force (m), N is the rotary speed of drill (rpm), A indicates the drilled area of hole (m^2), Pr represents the penetration rate (m min-1), and FN is the thrust force (N). In addition, work done per minute is determined using 2πRNFT + FNPr, and the volume of rock removed per minute is obtained using PrA.

3.5. Drilling experiments

In this research work, drilling tests were conducted to determine how the mechanical qualities of the rock, the physical qualities of the cooling lubricant, and the drilling rig operational parameters affect the drilling's specific energy, the most important indicator of drilling performance. The appropriate rotational speeds and thrust forces for drilling experiments were determined by trial and error. This procedure entailed conducting multiple pilot tests with minimum and maximum rig power and eliminating the settings that caused the drill bit to break or become stuck. Following this procedure for both hard and soft rocks, it was determined to conduct experiments with rotation speeds of 1190, 1057, and 933 rpm and thrust forces of 133, 116, 95, and 77 kg for the hard rock sample; and rotation speeds of 933, 845, 720, and 610 rpm and thrust forces of 116, 95, 77 and 58 kg for the soft rock sample.

Drilling experiments with the described operating conditions were performed on soft rock samples (A_4, A_5, A_6, and A_7) using water and five fluids (i.e. FS_1, FS_2, FSW_1, FSW_2, and FBN) as the cooling lubricant. After reviewing the data, two of these five fluids with the highest ROP were selected for drilling the hard rock samples. Thus drilling experiments on hard rock samples (A_1, A_2, and A_3) were conducted with the mentioned operating conditions while using two fluids: FS_1 and FSW_2. Overall, 192 drilling experiments with six fluids were performed on the collected marble samples, 192 on the collected travertine samples, and 108 with three fluids on the collected granite samples (492 drilling experiments in total). The tests were carried out to investigate the effect of mechanical characteristics of rocks, physical qualities of cooling lubricant, and operating parameters of the drilling rig on specific energy of drilling in seven hard and soft rock specimens. These experiments included using three cooling lubricants for hard rocks and six cooling lubricants for soft rocks.

4. Analysis of Experimental Results

Univariate linear regression was performed to examine the association between the specific drilling energy and the rock's mechanical characteristics, the cooling lubricant's physical qualities, and the drilling rig's operational parameters.

The correlation of mechanical parameters of the rock (UCS, SF-a, MH, and YM) and specific energy of drilling under constant operating conditions (thrust force of 77Kg and rotation speed of 933rpm) with FW, FS_1, and FSW_2 was analyzed through linear, power, exponential, logarithmic, and other functions. Accordingly, the function with the strongest correlation coefficient was determined.

Figures 3 to 6 show the correlation of specific energy with mechanical parameters of granite, marble, and travertine.

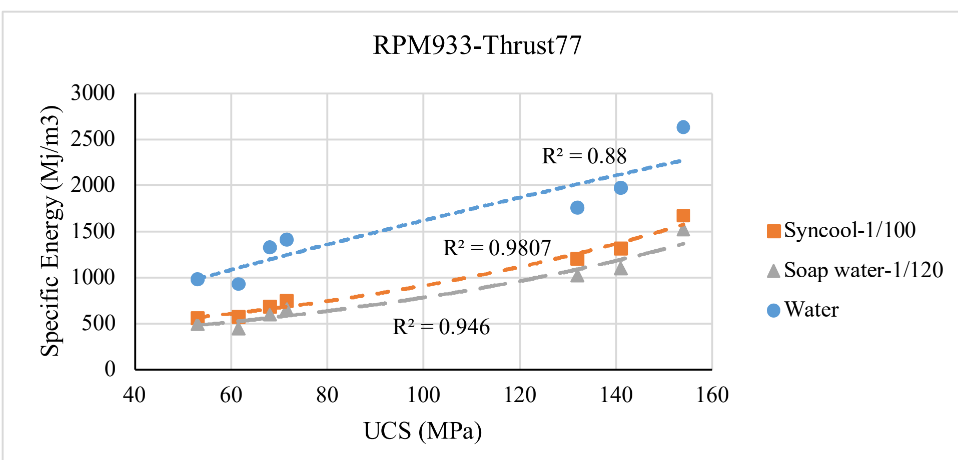

Figure 3. The relationship between UCS and specific energy of drilling with FW, FS_1, FSW_2 as cooling lubricants.

Figure 3 shows the significant power/exponential link between the specific energy and the rock's UCS. As shown in this figure, all data for all fluids show the same trend, i.e. an increase in specific energy with increasing UCS. This relationship is per the equations outlined below.

$SE_{FW} = 43.398UCS^{0.7859}$	$R^2 = 0.88$	(4)
$SE_{FS1} = 331.2e^{0.0101UCS}$	$R^2 = 0.98$	(5)
$SE_{FSW2} = 279.05e^{0.0103UCS}$	$R^2 = 0.94$	(6)

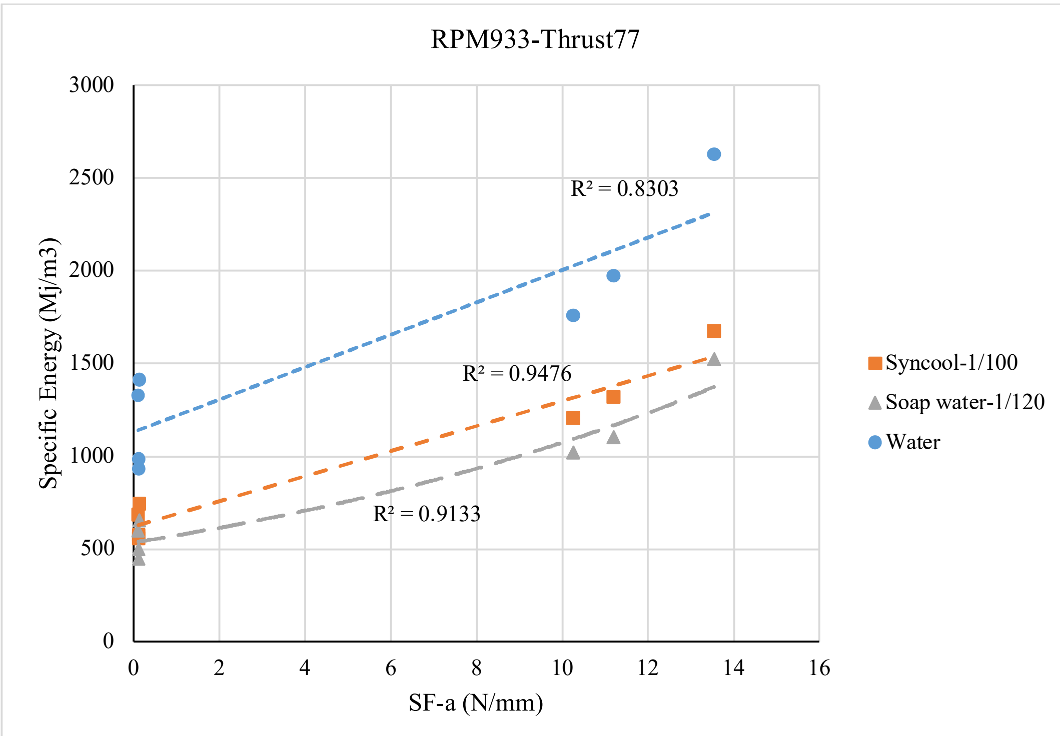

Figure 4. The relationship between SF-a and specific energy of drilling with FW, FS_1, and FSW_2 as cooling lubricants.

Figure 4 illustrates the strong linear/exponential link between the rock's specific energy and SF-a. As can be seen, data for all fluids have the same trend, indicating an increase in specific energy with increasing the SF-a. These relationships can be expressed using the following equations:

$SE_{FW} = 87.445SF\text{-}a + 1130.8$	$R^2 = 0.83$	(7)
$SE_{FS1} = 67.652SF\text{-}a + 621.73$	$R^2 = 0.94$	(8)
$SE_{FSW2} = 534.33e^{0.0698SF-a}$	$R^2 = 0.91$	(9)

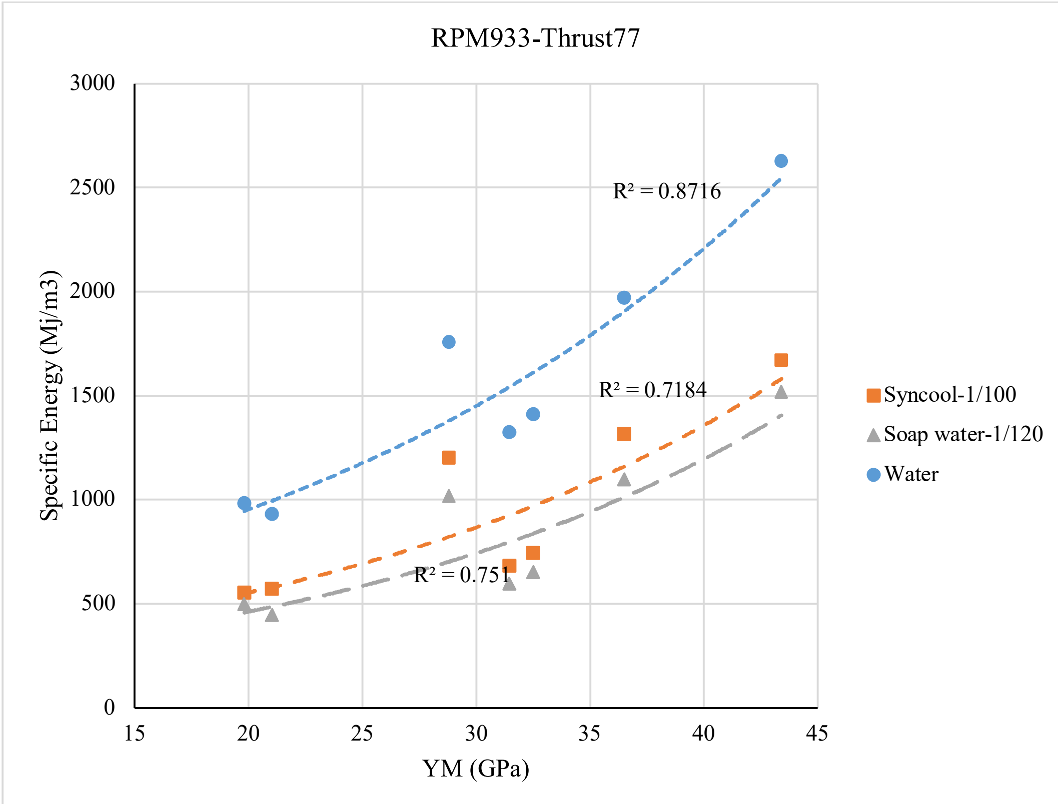

Figure 5. The relationship between YM and specific energy of drilling with FW, FS_1, and FSW_2 as cooling lubricants.

Figure 5 shows a strong exponential relationship between specific energy and the YM of the rock. As can be seen, data for all fluids exhibit an increase in specific energy with increasing the YM. This relationship is expressed by the following equations:

$SE_{FW} = 411.43e^{0.042YM}$	$R^2 = 0.87$	(10)
$SE_{FS1} = 225.64e^{0.0449YM}$	$R^2 = 0.71$	(11)
$SE_{FSW2} = 178.25e^{0.0476YM}$	$R^2 = 0.75$	(12)

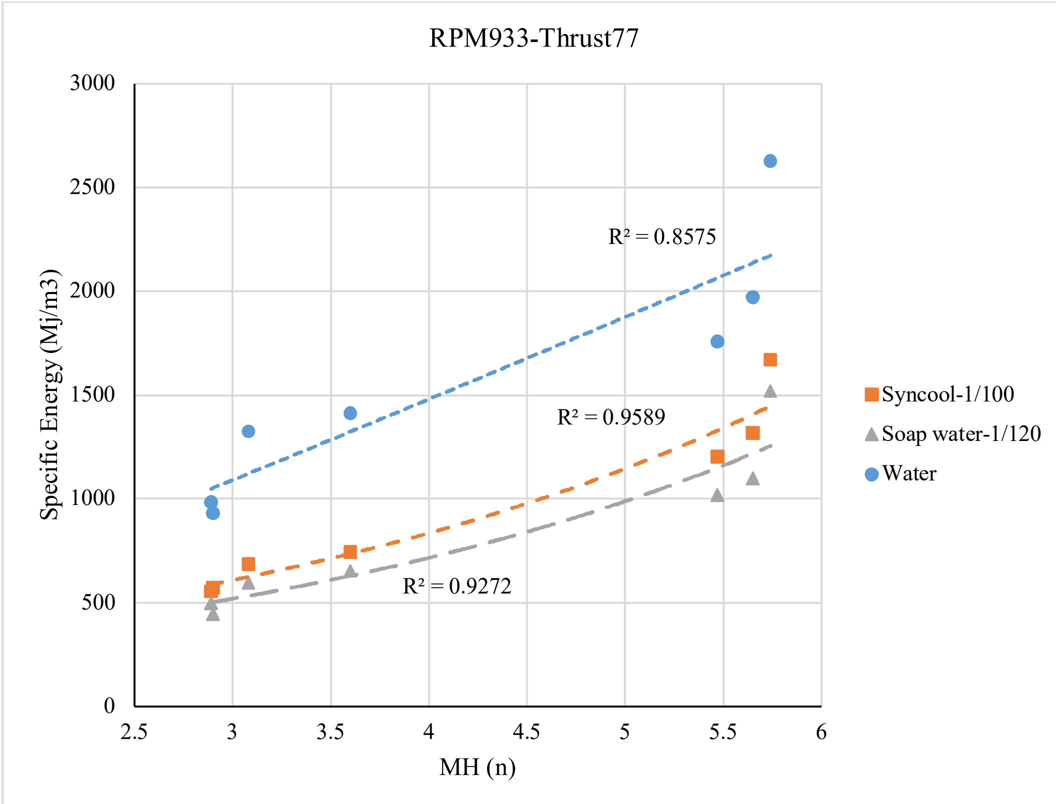

Figure 6. The relationship between MH and specific energy of drilling for FW, FS_1, and FSW_2 as cooling lubricants.

According to Figure 6, there is a significant power/exponential link between the specific energy and the rock's MH. As can be seen, data for all fluids show an increase in specific energy with increasing MH. This relationship is expressed using the following equations:

$$SE_{FW} = 339.25YM^{1.0628} \quad R^2 = 0.85 \quad (13)$$

$$SE_{FS1} = 235.51e^{0.3164YM} \quad R^2 = 0.95 \quad (14)$$

$$SE_{FSW2} = 196.83e^{0.3227YM} \quad R^2 = 0.92 \quad (15)$$

The correlation between physical parameters (i.e. Vis, pH, and EC) using FW, FS_1, and FSW_2 and the specific drilling energy under constant operating conditions (thrust force of 77 kg and rotation speed of 933 rpm). Figures 7-9 indicate the relationship between the physical parameters of cooling lubricants and the specific energy of drilling in granite, marble, and travertine.

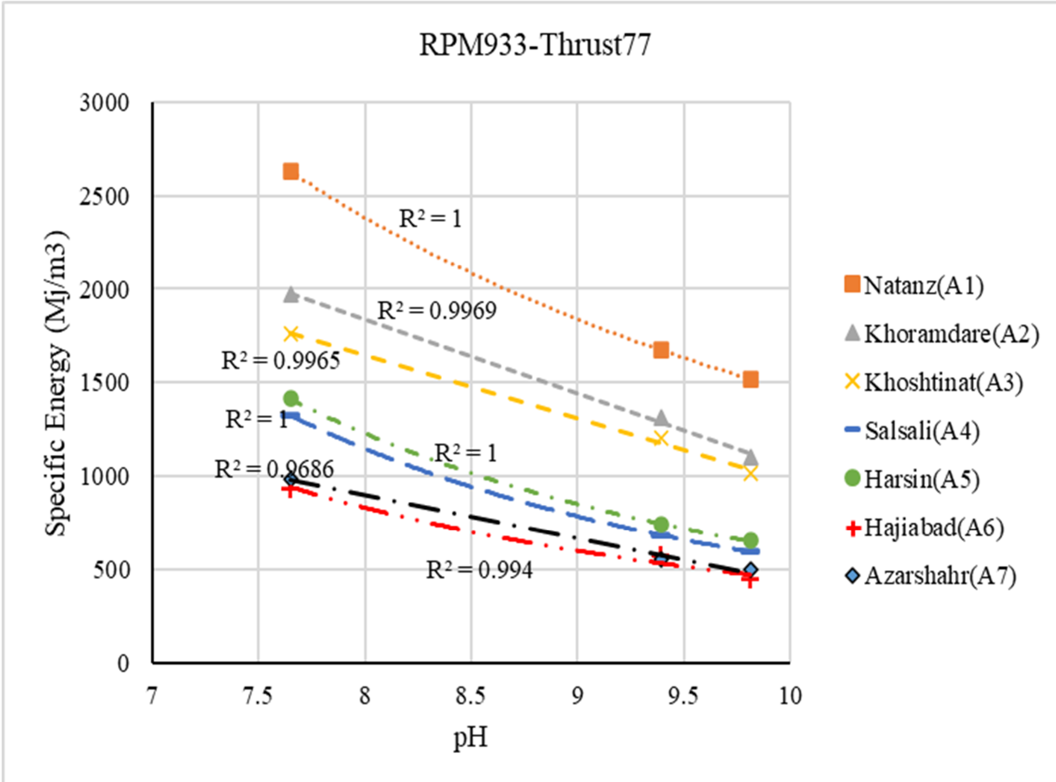

Figure 7. The relationship between the pH of cooling lubricants and the specific energy of drilling in granite, marble, and travertine.

Figure 7 represents a significant power/linear relationship between the pH of the cooling lubricant and the drilling's specific energy in the examined rock samples. As can be seen, the trends are similar for all cases, demonstrating a decrease in specific energy with the increase in pH values. This relationship follows the equations provided below:

$SE_{A1} = 232655 PH^{-2.203}$	$R^2 = 1$	(16)
$SE_{A2} = -396.38PH + 5011.9$	$R^2 = 0.99$	(17)
$SE_{A3} = -336.08PH + 4335.1$	$R^2 = 0.99$	(18)
$SE_{A4} = 923635 PH^{-3.217}$	$R^2 = 1$	(19)
$SE_{A5} = 786165 PH^{-3.107}$	$R^2 = 1$	(20)
$SE_{A6} = 266787 PH^{-2.774}$	$R^2 = 0.96$	(21)
$SE_{A7} = -231.44PH + 2750.7$	$R^2 = 0.99$	(22)

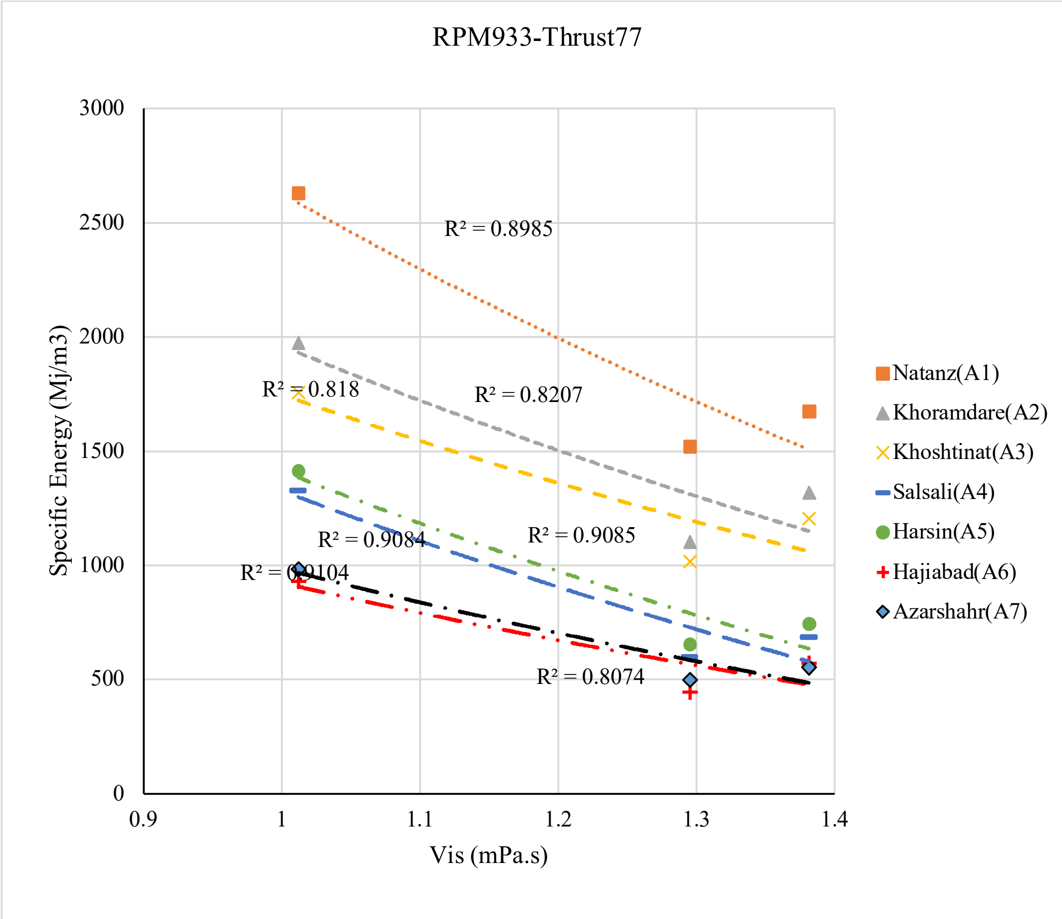

Figure 8. The relationship between the Vis of cooling lubricant and the specific energy of drilling in granite, marble, and travertine.

Figure 8 indicates a high correlation between the specific drilling energy in the examined rock materials and the Vis of the cooling lubricant in logarithmic form. In this figure, the trends are similar for all cases, representing a decrease in specific energy with increasing Vis values. These relationships are expressed by the following equations:

$SE_{A1} = -3472\ln(Vis) + 2627.6$	$R^2 = 0.89$	(23)
$SE_{A2} = -2510\ln(Vis) + 1960.6$	$R^2 = 0.82$	(24)
$SE_{A3} = -2125\ln(Vis) + 1747.4$	$R^2 = 0.81$	(25)
$SE_{A4} = -2314\ln(Vis) + 1326.7$	$R^2 = 0.90$	(26)
$SE_{A5} = -2408\ln(Vis) + 1413.2$	$R^2 = 0.90$	(27)
$SE_{A6} = -1546\ln(Vis) + 985.02$	$R^2 = 0.80$	(28)
$SE_{A7} = -1378\ln(Vis) + 922.85$	$R^2 = 0.91$	(29)

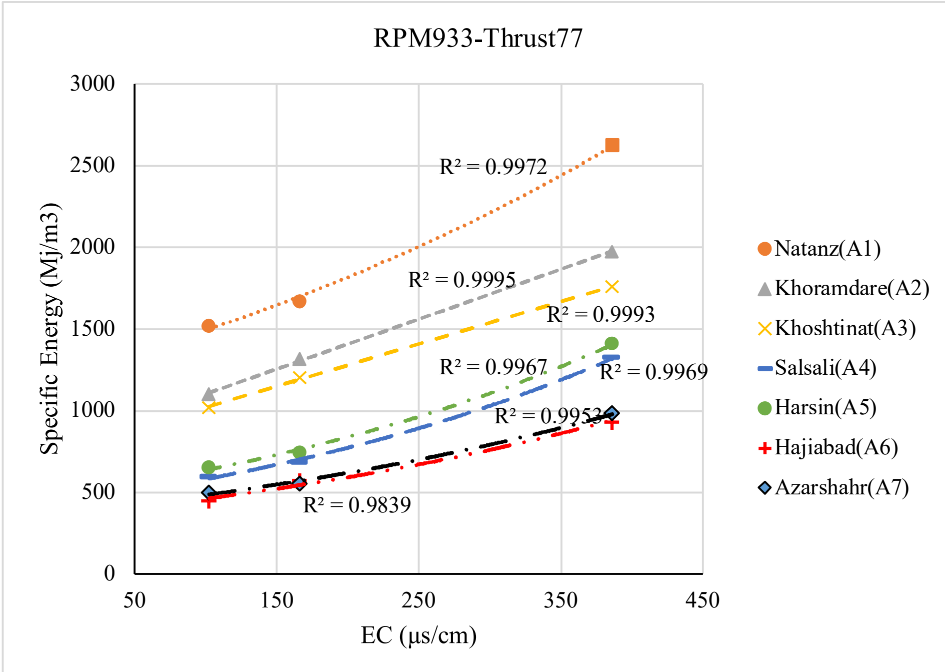

Figure 9. The relationship between the EC of cooling lubricant and the specific energy of drilling in granite, marble, and travertine.

Figure 9 illustrates a significant exponential/linear relationship between the specific drilling energy in the examined rock samples and the EC of the cooling lubricant. As can be seen, the trends show an increase in specific energy with the increase in EC. This relationship is expressed using the equations provided below:

$SE_{A1} = 1227.2e^{0.002EC}$	$R^2 = 0.99$	(30)
$SE_{A2} = 3.0566EC + 796.99$	$R^2 = 0.99$	(31)
$SE_{A3} = 2.5919EC + 761.37$	$R^2 = 0.99$	(32)
$SE_{A4} = 435.84e^{0.0029EC}$	$R^2 = 0.99$	(33)
$SE_{A5} = 482.21e^{0.0028EC}$	$R^2 = 0.99$	(34)
$SE_{A6} = 359.54e^{0.0025EC}$	$R^2 = 0.98$	(35)
$SE_{A7} = 379.26e^{0.0025EC}$	$R^2 = 0.99$	(36)

Statistical methods of scatter plot analysis, the 1:1 line, and the estimation error index were used to validate and evaluate the obtained results. These results were extracted from the relationship between specific energy and the mechanical characteristics of the rock, the physical properties of the fluid, and the operational parameters of the device in seven rock samples drilled using coolant and lubricant fluids. Based on this statistical method, the relationship between specific energy and the mechanical characteristics of the rock and physical properties of the fluid is stronger and more accurate when the estimation error is lower, the point density is closer to the 1:1 line, and the correlation coefficient is higher.

Figures 10 to 13 depict scatter plots of predicted and observed values of specific energy concerning the mechanical properties of the rock under the conditions of the three fluids studied: FW, FS_1, and FSW_2.

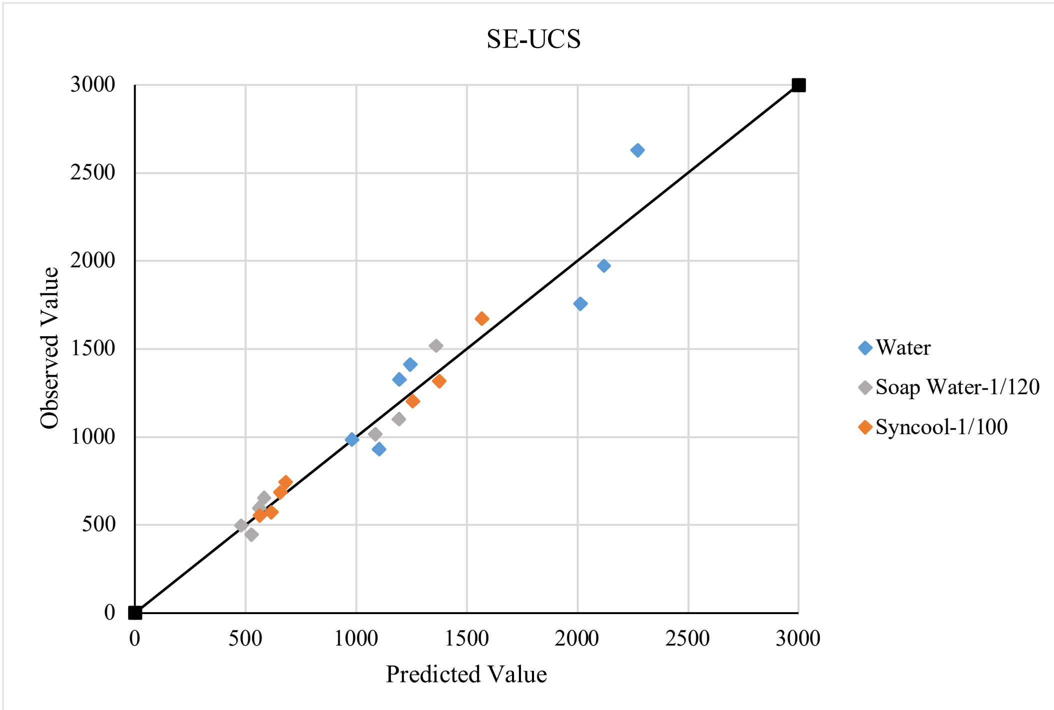

Figure 10. Scattering plot of predicted and observed values of specific energy relative to the 1:1 bisector line for the UCS parameter.

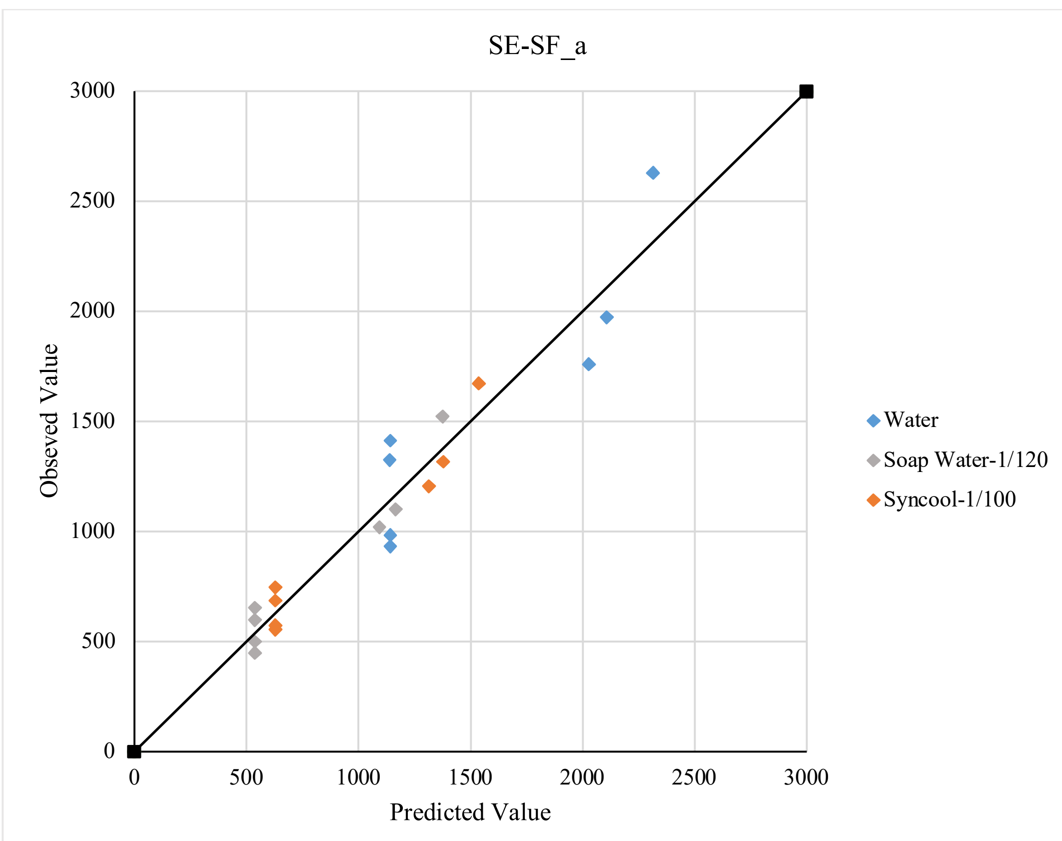

Figure 11. Scattering plot of predicted and observed values of specific energy relative to the 1:1 bisector line for the SF-a parameter.

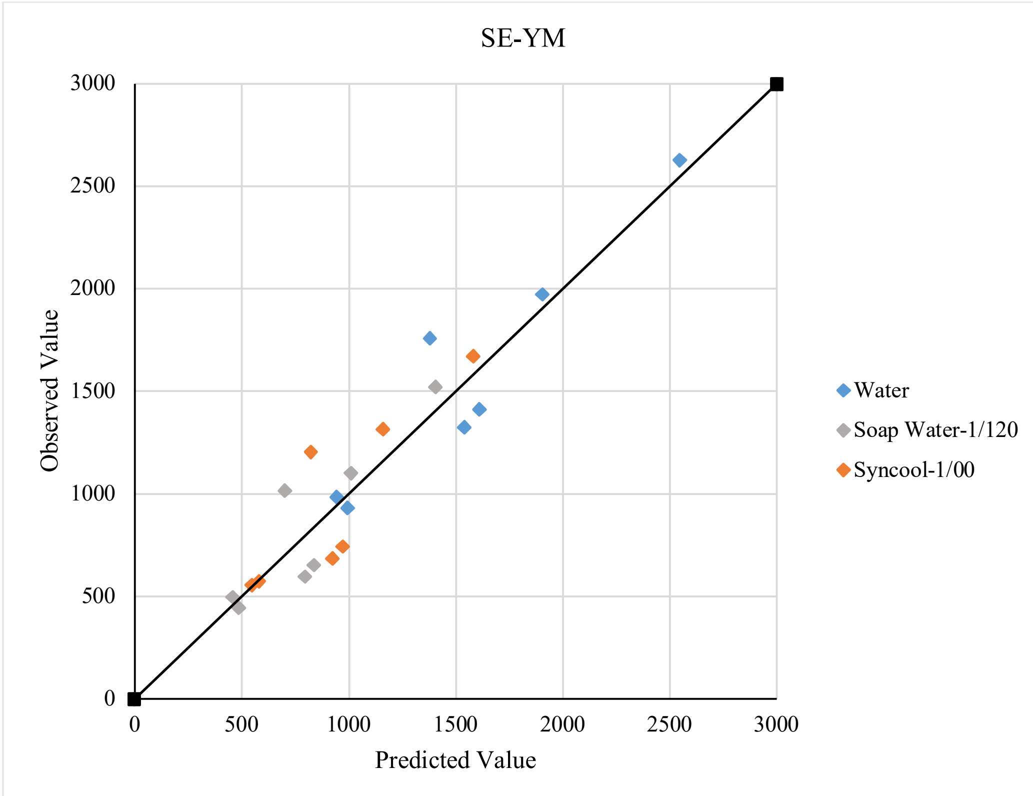

Figure 12. Scattering plot of predicted and observed values of specific energy using the 1:1 bisector line for the YM parameter.

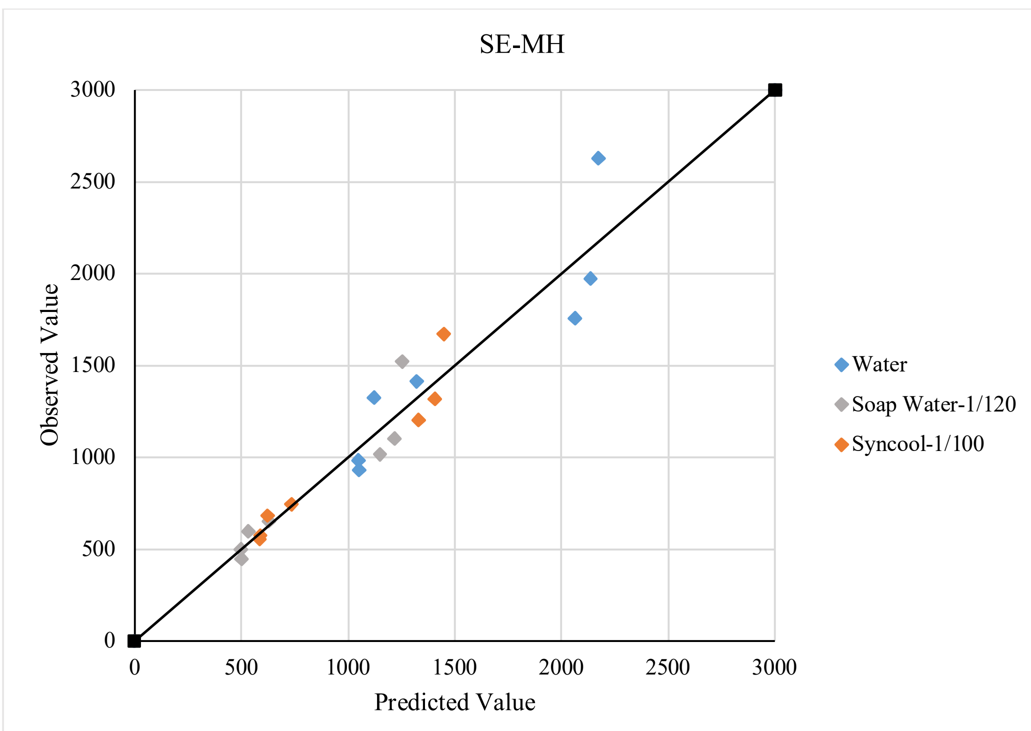

Figure 13. Scattering plot of predicted and observed values of specific energy using the 1:1 bisector line for the MH parameter.

Figures 14 through 16 depict scatter plots of predicted and observed values of specific energy in relation to the physical properties of the fluid under the conditions of the three fluids studied: FW, FS_1, and FSW_2.

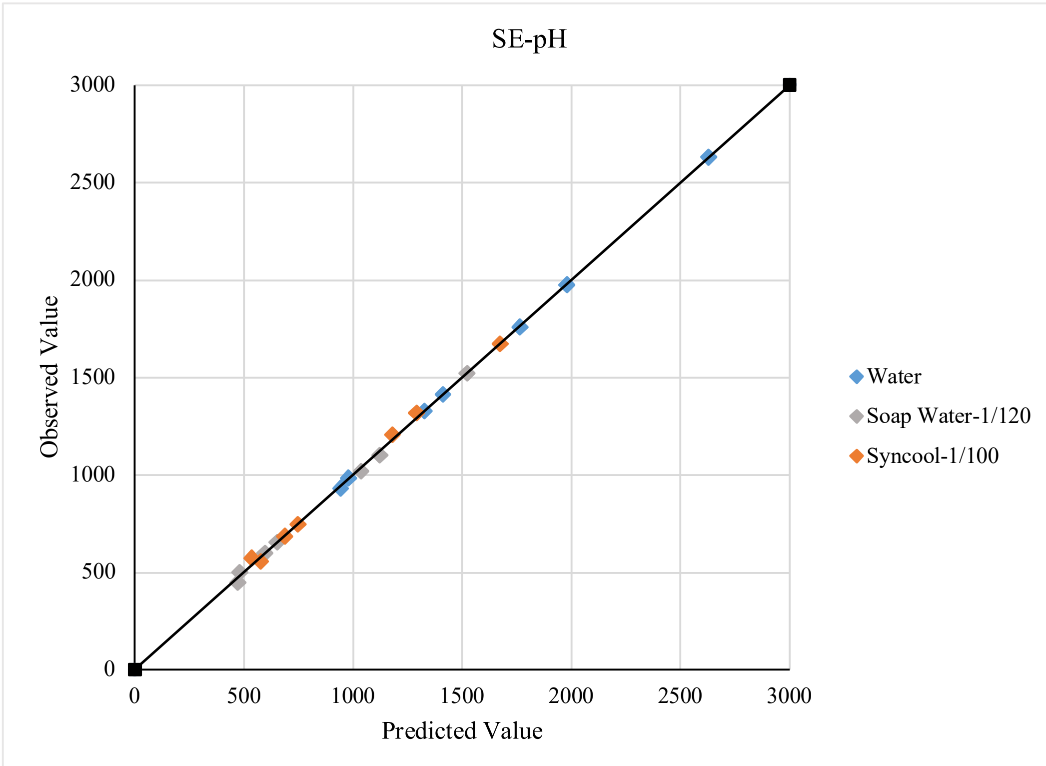

Figure 14. Scattering plot of predicted and observed values of specific energy relative to the 1:1 bisector line for the pH parameter.

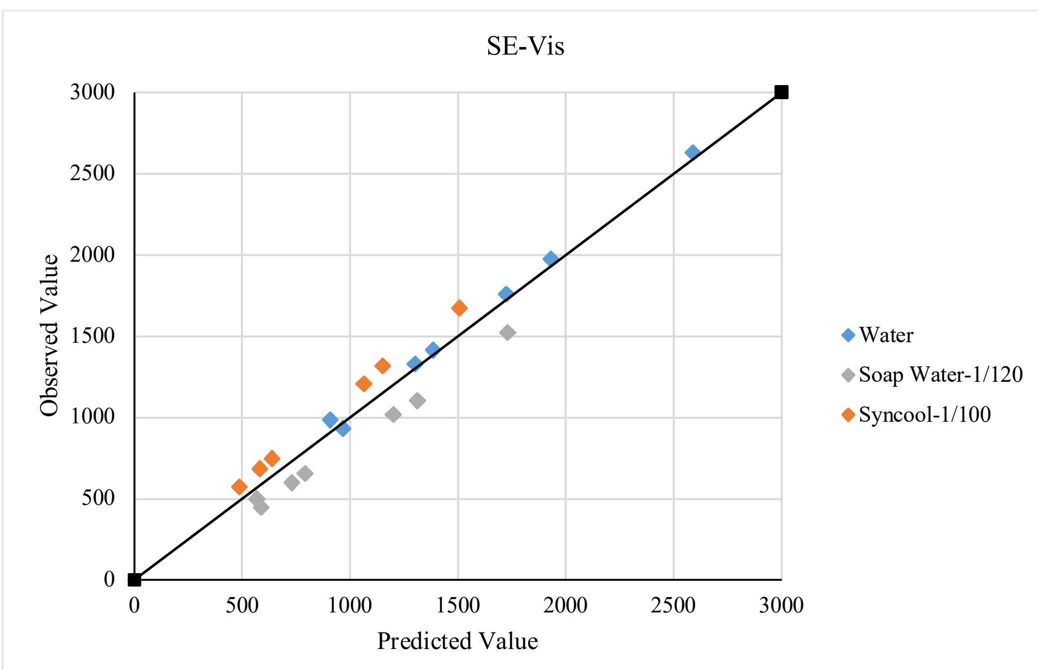

Figure 15. Scattering plot of predicted and observed values of specific energy relative to the 1:1 bisector line for the Vis parameter.

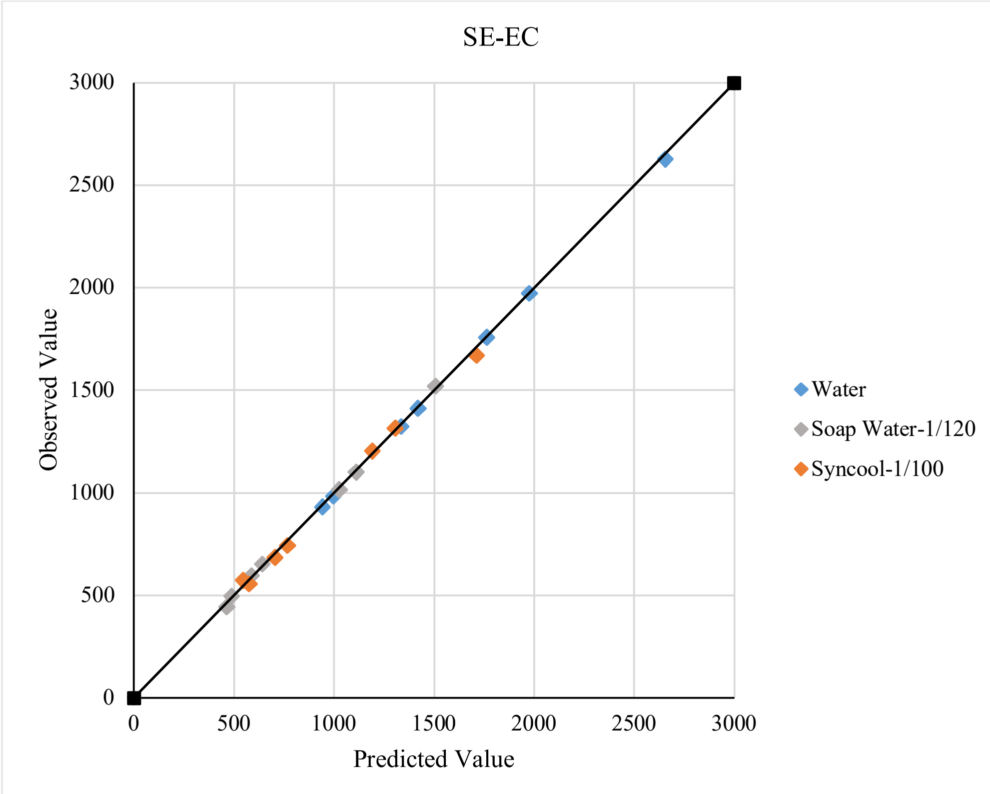

Figure 16. Scattering plot of predicted and observed values of specific energy relative to the 1:1 bisector line for the EC parameter.

Figure 16 presents the scatter plots for the dispersion of predicted and actual values of specific energy relative to the 1:1 line. As can be inferred, the drilling-specific energy is highly correlated with the mechanical characteristics of the rock and the physical properties of the fluid under the conditions of using the studied coolant and lubricant fluids.

5. Discussion

To date, scarce research has been conducted on the impact of coolant and lubricant fluids on specific energy or overall drilling performance. The studies conducted in this field on the influence of operational parameters of the drilling system using coolant and lubricant fluids (additives to water-based fluids) on drilling performance have yielded similar results. These studies demonstrate that increasing the back pressure up to a certain limit lowers the specific energy. Meanwhile, after reaching a certain threshold, increasing the back pressure causes the specific energy to increase. However, no significant relationship has been established regarding the effect of changes in the rotational drilling speed on specific energy. The present study also reached similar conclusions. Subsequently, it was decided to examine the impact of the mechanical characteristics of the rock and the physical properties of the fluid on specific energy when using coolant and lubricant fluids.

This study first investigated the relationship between specific energy and mechanical properties of the drilled rock. The results of statistical analyses revealed a strong relationship with a high correlation coefficient between specific energy and mechanical parameters of the rock. Moreover, it was found that under constant conditions in terms of mechanical properties and operating parameters, using FS_1 instead of FW reduced specific energy by 34% in the granite samples, 48% in the marble samples, and 41% in the travertine samples. Moreover, using FS_2 instead of FW led to a 43% reduction in specific energy in the granite samples, 54% in the marble samples, and 50% in the travertine samples. The statistical analysis of the relationship between specific energy and physical characteristics of the studied cooling lubricants also revealed a strong relationship with a very high correlation coefficient between these parameters. In this regard, specific energy showed a direct relationship with EC and an inverse relationship with Vis and pH. The reduction in specific energy was greater when using FS_1 and FSW_2 than when using FW as the cooling lubricant. Among the tested cooling lubricants, FSW_2 was the most effective one in reducing specific energy. Overall, the results showed the good performance and high effectiveness of cooling lubricants in reducing specific energy. Considering the negative impact of undesirable process forces (tangential and vertical forces applied on the drill bit), thermal stresses, and cuttings in the drilling environment on the drilling performance, it can be concluded that much of the energy consumed during drilling operations is converted into thermal stress through friction at the bit-rock interface. This process intensifies with increasing the mechanical properties of the rock, including uniaxial compressive strength, hardness, abrasivity, and Young's modulus. Therefore, it is necessary to lower the specific energy of drilling and the drill bit wear rate. To this end, it is required to not only limit process forces but also decrease the thermal stresses generated by drill bit-rock interactions. One of the most effective ways to achieve this goal is to inject a suitable cooling lubricant into the drilling environment. Additionally, incorporating cooling and lubricant fluids lowers the vibration of drilling machines. As a result, it lowers maintenance costs and decreases the overall project expenses. The present study showed that using FS_1 and FSW_2 as the cooling lubricant reduced friction at the bit/rock interface and accelerated the removal of cuttings from the drilling environment. Accordingly, it reduced process forces and thermal stresses and decreased the energy consumed during drilling, thereby increasing the drilling efficiency.

In this study, the correlation between specific energy and parameters related to the mechanical characteristics of the rock and the physical properties of the fluid was validated using the estimation error index. Examining the association of specific energy and parameters related to the mechanical characteristics of the rock under the conditions of using coolant and lubricant fluids revealed that UCS established a stronger relationship with a lower estimation error for specific energy. This relationship resulted in an estimation error of 10% when using FW fluid, 5% using FS_1 fluid, and 9% using FSW_2 fluid. Hence, the average estimation error for the UCS parameter of the rock is estimated to be 8%.

MH parameter is the next parameter that exhibited a better correlation and a lower estimation error for specific energy. The estimation error was 12% when using FW fluid, 7% when using FS_1 fluid, and 9% when using FSW_2 fluid. Thus, the mean estimation error for the rock's MH parameter is 9%.

The SF-a parameter is associated with a higher estimation error for specific energy. The estimation error was 15% when using FW fluid, 10% when using FS_1, and 11% when using FSW_2. Therefore, the average estimation error is 12% for the SF-a parameter of the rock.

Lastly, YM exhibited the least correlation with the highest estimation error for specific energy. The estimation error was 10% when using FW, 17% when using FS_1, and 18% when using FSW_2. Therefore, the average estimation error for the YM parameter of the rock is estimated to be 15%.

In the following, the relationship between specific energy and parameters relating to the physical properties of the fluid under the conditions of using refrigerant and working fluid was investigated. The results revealed that pH has a stronger correlation with a smaller specific energy estimation error. Specifically, an estimation error of 0.5% was obtained when using the FW fluid, 2% when using fluid FS_1, and 2% when using the FSW_2. Therefore, the average estimation error for the pH parameter of the fluid is 1.5%.

EC is the next parameter exhibiting a better correlation and lower specific energy estimation error. A 1% estimation error was observed when using the FW fluid, 3% when using FS_1, and 2% when using FSW_2. Therefore, the average estimation error for the EC parameter of the fluid is 2%.

Finally, the Vis parameter exhibits a weaker correlation and higher estimation errors with specific energy. Furthermore, 3%, 13%, and 19% estimation errors were obtained when using the FW, FS_1, and FSW_2, respectively. Therefore, the average estimation error for the Vis parameter of the fluid is 12%.

6. Conclusions

The present study conducts a series of drilling experiments and statistical analyses to investigate the relationship of specific energy of drilling with the physical properties of the drilled rock, the physical properties of the cooling lubricant, and the operating parameters of the drilling rig. First, the most important mechanical properties of the collected rock samples and relevant physical properties of the chosen cooling lubricants were measured. Afterward, a laboratory-scale drilling rig was used to perform drilling experiments on seven rock samples (three granite samples, two marble samples, and two travertine samples).

Meanwhile, six fluids (water and five cooling lubricants) were used to cool and lubricate the drilling environment. The results of univariate linear regression analysis of the experimental data revealed a direct relationship between the specific energy of drilling and the mechanical properties of the drilled rock. The results showed an increase in specific energy with an increase in UCS, Schmiazek abrasiveness factor, Mohs hardness, and Young's modulus. The rate of change and the percentage reduction in specific energy were different for different fluids. Under constant conditions in terms of mechanical properties and operating parameters, using FS_1 and FSW_2 as the cooling lubricant instead of water (FW) resulted in 34% and 43% reductions in specific energy in the granite samples, 48% and 54% i in the marble samples, and 41% and 50% in the travertine samples, respectively. The results also showed that under constant conditions in terms of mechanical properties and operating parameters, there is a strong relationship with a very high correlation coefficient between the specific energy of drilling and the physical properties of the fluid used as the cooling lubricant. Overall, the experiments' results showed that under constant conditions in terms of the mechanical properties of the rock, physical properties of the cooling lubricant, and operating parameters of the drilling rig, using FS_1 and FSW_2 instead of FW decreased the specific energy of drilling by on average 39 % and 47%, respectively. According to these values, FSW_2 was slightly more effective than FS_1 and extremely effective than FW in improving the specific drilling energy in the studied rock samples. Overall, the results suggest that a significant improvement in specific energy can be achieved by using mixed cooling-lubricating fluids like FS_1 and FSW_2 rather than conventional fluids like FW.

This study validated the results by comparing the estimation error index using the scatter plots prepared for predicted and actual values with a 1:1 line. Investigating the relationship between specific energy and mechanical properties of rocks when using drilling fluids and work fluids demonstrated that specific energy is better correlated with UCS based on the average estimation error. It then demonstrated a stronger relationship with MH and SF-a and exhibited the weakest correlation with the parameter MY. Furthermore, examining the relationship between specific energy and the physical properties of the fluid when using drilling and work fluids indicated that specific energy is better correlated with pH based on the average estimation error. In the next ranks, it displayed a better relationship with EC and had the least correlation with Vis. Based on the studies and experiments conducted, it can be concluded that a high-efficiency drilling operation is characterized by the minimization of specific energy when considering rock properties, fluid characteristics, and operational parameters. One of the most important solutions to achieve this goal is using cooling and lubricating fluids in the drilling environment.

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

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چکیده:

انرژی ویژه اصلی‌ترین شاخص در بررسی عملکرد حفاری می‌باشد بنابراین با توجه به اینکه عملکرد حفاری یکی از مهمترین پارامترهایی است که هنگام ارزیابی امکان سنجی و اقتصاد پروژه مورد توجه قرار می‌گیرد. هر گونه بهبود در فرایند حفاری به صورت کاهش انرژی ویژه با توجه به خواص سنگ و پارامترهای عملیاتی، نشان دهنده یک عملیات حفاری با راندمان بالا می‌باشد که یکی از مهم‌ترین راه کارها برای دست‌یابی به این هدف استفاده از یک سیال خنک کننده و روان کار مناسب در محیط حفاری می‌باشد. در این تحقیق به بررسی تاثیر و ارتباط میان مشخصات مکانیکی سنگ، مشخصات فیزیکی سیال خنک کننده و روانکار و همچنین پارامترهای عملیاتی دستگاه با انرژی ویژه در شرایط استفاده از سیال آب و ۵ نمونه سیال خنک کننده و روانکار بر روی ۷ نمونه سنگ شامل سنگ‌های گرانیتی و مرمریت و تراورتن پرداخته شده است. برای انجام آزمایشات حفاری یک دستگاه حفاری در مقیاس آزمایشگاهی طراحی و ساخته شد و تعداد ۴۹۲ تست در شرایط عملیاتی مختلف بر روی نمونه‌های سنگی مکعبی برای اندازه‌گیری میزان انرژی ویژه انجام شده است. پس از انجام آزمایش‌های حفاری و تهیه جامعه آماری، نتایج حاصل از مطالعات آماری تک متغیره خطی نشان داد میزان انرژی ویژه در شرایط استفاده از سیالات خنک کننده و روانکار نسبت به شرایط معمول حفاری کاهش قابل توجهی پیدا کرده است به گونه‌ای که میزان انرژی ویژه 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 صورت میانگین ۳۴٪ و ۴۳٪ و در نمونه سنگ‌های مرمریت ۴۸٪ و ۵۴٪ و در نمونه سنگ‌های تراورتن ۴۱٪ و ۵۰٪ کاهش پیدا کرده است. این تغییرات در کاهش میزان انرژی ویژه نشان می‌دهد که استفاده از سیال خنک کننده و روانکار مناسب باعث افزایش راندمان و عملکرد حفاری می‌شود.

کلمات کلیدی: حفاری، انرژی ویژه، سیال خنک کننده و روانکار، عملکرد حفاری، مطالعات آماری، تک متغیره خطی.