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ORIGINAL ARTICLE

Investigation of fracture properties of rocks under drilling fluid saturation

Hasan Karakul[1]

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Abstract
The invasion created by drilling fluids around borehole walls creates considerable variations on mechanical and physical properties of both rock materials and discontinuities. However, up to date there is no comprehensive study has been performed on the variation of fracture toughness values of rocks under drilling fluid saturation with different compositions. By considering this deficiency, the variation of fracture toughness values of five different rocks interacting with drilling fluids with different compositions was investigated in this study. The experiments showed that the negative effect of drilling fluids on fracture toughness values of rocks has a broad range and the addition of polymers to the drilling fluid prevents a dramatic decrease in the fracture toughness values of rocks. Statistical evaluations showed that the fracture toughness values of rocks can be predicted from tensile strength with moderate error by simple regression analyses. However, the multivariate regression analyses produced statistically significant prediction equations with stronger coefficients of determination. On the other hand, the prediction capability of Adaptive Neuro Fuzzy Inference System (ANFIS) model was higher than the prediction performance of simple and multivariate regression analyses.

Keywords Drilling fluid · Fracture toughness · Rock mass · Discontunity · Drilling fluid · Hydraulic fracturing · Multivariate regression analysis

Introduction

Fracture toughness is a fracture-mechanical parameter for classifying rock materials (Gunsallus et al. 1984), hydraulic fracturing (Rummel and Winter 1982; Takashi 1983), explosive stimulation of gas wells (Travis and Davis 1980), stability analysis (Kemeny and Cook 1985) and index of rock fragmentation processes (Lindqvist 1982). Fracture creation in rock formations around boreholes, which is an application used in hydraulic fracturing, is related to the fracture toughness of rocks. Fracture initiation pressure for the impermeable condition in a vertical well is given in the following equation (Fjaer et al. 2008):

$$p_{w,\max^{\text{frac}}} = 3\sigma_h - \sigma_H - p_f + T_0 \quad (1)$$

✉ Hasan Karakul
hasan.karakul@ikcu.edu.tr

[1] Department of Petroleum and Natural Gas Engineering, İzmir Kâtip Çelebi University, 35620 Çiğli, İzmir, Turkey

where σ_h is smallest principal stress, σ_H is intermediate principal stress, p_f is pore pressure and T_0 is tensile strength.

However, if there is a preexisting crack oriented parallel to the highest principal stress (σ_1) and perpendicular to the lowest principal stress (σ_3), borehole breakdown pressure is given by the following equation (Abou-Sayed et al. 1978):

$$P_B \approx \frac{1}{2}(3\sigma_3 - \sigma_1 + \frac{K_{\text{IC}}}{0.6\sqrt{\pi a_0}}) \quad (2)$$

where K_{IC} is Mode-I fracture toughness, a_o is length of preexisting crack, σ_1 and σ_3 are maximum and minimum principal stresses, respectively.

Rummel (1987) gives another equation related to critical borehole pressure which is shown below:

$$p_c = \frac{1}{h_0 + h_a}(\frac{K_{IC}}{\sqrt{R}} + S_H f + S_h g) \quad (3)$$

where K_{IC} is Mode-I fracture toughness, h_o, h_a, f and g are dimensionless stress intensity functions, R is the radius of a circular hole, S_H and S_h are the principal horizontal far field stresses.

In addition to application for hydraulic fracturing, fracture toughness is also an essential input parameter for prediction of rock cutting performance. The critical energy release rate which is a indicator of required energy level to create new surface area can be defined with following equation (Nelson et al. 1985).

$$G_{IC} = \frac{{K_{IC}}^2(1 - \upsilon^2)}{E} \quad (4)$$

where K_{IC} is the fracture toughness, E is Young modulus and ν is Poisson's ratio.

So it is obvious that rock cutting performance is directly related to rock fracture toughness. By considering this situation, Ingraffea et al. (1982) and Nelson et al. (1985) tried to obtain relationship between TBM (Tunnel Boring Machine) performance and rock fracture properties as fracture toughness and critical energy release rate. Guo (1990) measured the performance of a diamond coring machine and rotary drilling machine for six different rock types and compared the penetration rates with fracture toughness of tested rocks. Guo (1990) stated that there is a non-linear and strong relationship between penetration rate of diamond coring machine and fracture toughness values of tested rocks. The similar relationship with stronger coefficient of determination between penetration rate of rotary drilling machine and fracture toughness was also established by Guo (1990). By considering the study performed by Guo (1990), it can be inferred that penetration rate is inversely proportional to fracture toughness of rocks. The author also stressed that fracture toughness is recommended to predict the rock drilling performance predictions. However the authors focused on rock cutting performance did not consider the drilling fluid effects on fracture toughness values.

It is clear from the studies given above that the fracture toughness is an important input parameter for a great number of engineering applications. So the precise determination of fracture toughness is essential for different engineering applications. There are a few parameters (confining stress, temperature, anisotropy, saturation, loading rate, test specimen type, crack size and shape, mineralogy, size of specimen, etc.) that control the fracture toughness values of rocks.

The effect of size of specimen was studied by a few researchers (Bazant 1984; Bazant et al. 1991; Ayatollahi and Akbardoost 2012, 2013). Bazant (1984) stated that size effect for concrete structures or rock masses depends on the area and length of the crack band. The author also stressed that main mechanism to cause size effect is fracture-front blunting of any type rather than microcracking. Bazant et al. (1991) used size effect method which was previously developed for concrete, mortar and granite and emphasized that the method was also verified for limestone. Ayatollahi and Akbardoost (2012) developed a new stress-based criterion to determine the size effects on fracture toughness. The authors used limestone and concrete to validate the suggested criterion. Ayatollahi and Akbardoost (2012) found that size dependency of fracture toughness can be estimated for concrete using the new stress-based criterion. On the other hand, Ayatollahi and Akbardoost (2013) used a stress-based criterion to predict Mode II fracture resistance of intact rocks by considering the specimen size. The authors found that high quality prediction of Mode II fracture resistance of marble could be performed from Mode I fracture resistance by proposed criterion.

While there are a great number of studies (Atkinson et al. 1982; Bazant 1984; Bazant et al. 1991; Wang and Xing 1999; Al-Shayea et al. 2000; Khan and Al-Shayea 2000; Al-Shayea 2002; Atahan et al. 2005; Ke et al. 2008; Keles and Tutluoglu 2011; Ayatollahi and Akbardoost 2012; Ayatollahi and Akbardoost 2013; Asadi et al. 2013; Stöckhert 2015; Stoeckhert et al. 2016; Xu et al. 2017) on the variation of fracture properties in terms of confining stress, mineralogy, temperature, anisotropy, loading rate, test specimen type, crack size and shape, size of specimen; the saturation effect was only studied by a limited number of investigators (Roy et al. 2017a; Meng et al. 2018; Hua et al. 2019) and none of these focussed on saturation created by different drilling fluids.

Drilling fluids are used for different kinds of wells (geotechnical, geothermal, oil and natural gas, etc.) and the saturation created by invasion of drilling fluids into geological formations around the borehole is time dependent. Bassiouni (1994) stated that mud filtrate displaces formation fluids and almost the entire invasion is completed within a few hours. Zhang (2017) stated that the invasion process is closely related to formation and fluid properties. Zhang (2017) stressed that invasion process depends on a few parameters as permeability, porosity, original saturation, viscosity, salinity, capillary pressure, etc. While high values of permeability mean deeper invasion zones, higher porosity values refer to lower invasion depths (Zhang 2017). Permeability parameter is directly related to existence of fractures in rock masses. Jianmin and San (2018) stated that good migration paths are possible due to existence of micro-fractures and drilling fluids can reach deep into the reservoir. So it can be understood that existence of fractures is directly effective on the depth of invasion in different rocks and consideration of drilling fluid saturation for fracture toughness tests is essential.

Van Oort (2003) stressed that there are three mechanisms (chemical-based weakening of bonds, pore pressure and swelling pressure increment) related to instability of shales due to exposure to drilling fluids. Van Oort (2003) also stated that these processes create variations in effective stresses and strength parameters of rocks. So it is clear that the interaction between geological materials and drilling fluids due to invasion of drilling fluids into geological units located around boreholes cause significant variations in the values of geomechanical properties of rocks.

As stressed above, saturation effects on fracture toughness was only studied by a limited number of researchers. Hua et al. (2017) stated that fracture toughness values decrease greatly as a result of periodic water rock interactions for sandstone samples. So it is clear that Mode I and Mode II fracture toughness values of rocks are sensitive to saturation. By considering the photomicrographs of SEM analysis conducted on sandstones, Hua et al. (2017) indicated that rock pores tend to increase as a result of prolonged immersion and cyclic wetting and drying. In addition to this, SEM analysis also reveals that there is an increment of size and quantity of microcracks and weakening of adhesive forces between grains due to saturation-induced physical and chemical processes (Hua et al. 2017). However, the investigators used only water as a saturation fluid and the saturation created by drilling fluids was not studied within the context of their study. Meng et al. (2018) expressed that while gypsum specimens saturated by saline brine exhibited more plastic behaviour, dry specimens showed brittle behaviour. The investigators also stressed that the peak values of Mode I fracture toughness were reduced after treatment with half-saturated brine. However, Meng et al. (2018) did not use any drilling fluids to saturate the rock specimens.

Roy et al. (2017a) investigated the effect of water saturation on pure and mixed mode fracture toughness of sedimentary rocks. While decrement of mode I fracture toughness was found between 31.8 and 53%, the decrement of mixed-mode fracture toughness was measured between 16.2 and 44%. On the other hand, the reduction determined for mode-II fracture toughness was between 10.9 and 45.2%. The author also stated that two main mechanisms that create decrement on fracture toughness vakues were lubrication and weakening of bond between the grains.

It is clear from previous studies that the effect of drilling fluids on rock fracture toughness has not been studied yet. So, this is the novelty for this study which considers the drilling fluids effect on fracture properties of different rock types. However, there are a few studies (Ewy et al. 2008; Yan et al. 2013; Yu et al. 2013; Mkpoikana et al. 2015; Liu et al., 1998; Karakul 2018) focussed on drilling fluid effects on some mechanical properties of geomaterials other than fracture toughness, all of which stressed that considerable effects on mechanical properties of geomaterials were observed as a result of saturation by drilling fluids. Karakul (2018) stated that mechanical properties of rocks are changed due to interaction between rocks and drilling fluids, and the variation level is linked to the content of drilling fluids used in boreholes. On the other hand, Karakul and Ulusay (2013) defined a parameter (Effective Clay Content) which controls the level of adverse effect induced by saturation with water. However, the authors did not use drilling fluids to saturate the rock materials.

In consideration of the substantial invasion depth of drilling fluid (Zhang 2017) observed around borehole walls and the absence of research in the field, this study mainly focussed on the determination of the variation in fracture toughness values of various rocks under saturation by drilling fluids which are widely used in engineering practices.

On the other hand, the difficulities related with preparation of specimens according to standard or suggested methods, high cost and time consuming sample preparation process led researchers (Haberfield and Johnston 1989; Whittaker et al. 1992; Zhang et al. 1998; Zhang 2002; Jin et al. 2011) to perform statistical evaluations to predict fracture toughness values from geomechanical properties such as tensile strength. This study also aimed to estimate fracture toughness from tensile strength and other properties using simple, multivariate regression analyses and a soft computing method (ANFIS) because of existence of difficulities mentioned above. The novelty of this study is the derivation of prediction equations for K_{IC} and K_{IIC} by considering the drilling fluid saturation which has not been considered up to date.

Material and methods

Rock types

In this study, five rock types (one volcanic, two sedimentary and two volcano-sedimantary rocks) were used in the rock mechanics experiments (Fig. 1). Rock blocks, which were collected from stone-processing plants in Turkey, have no visible sign of disintegration and fractures. The distribution of sampling locations of rock blocks was given in Fig. 2. The rocks used in the experimental studies were examined petrographically using thin sections prepared from rock samples at the laboratories of the General Directorate of Mineral Research and Exploration of Turkey (MTA). Petrographical names and micrographs of the tested rocks are given in Table 1. The rocks studied were also examined by XRD analyses at the Center for Fabrication and Application of Electronic Materials of Dokuz Eylül University to obtain whole sample mineralogy. XRD results were given in Table 2. The mineral content of rocks used in this study was predicted using the method suggested by Gündoğdu (1982). XRD difractograms of Ignimbrite and tuff units are given in Fig. 3.

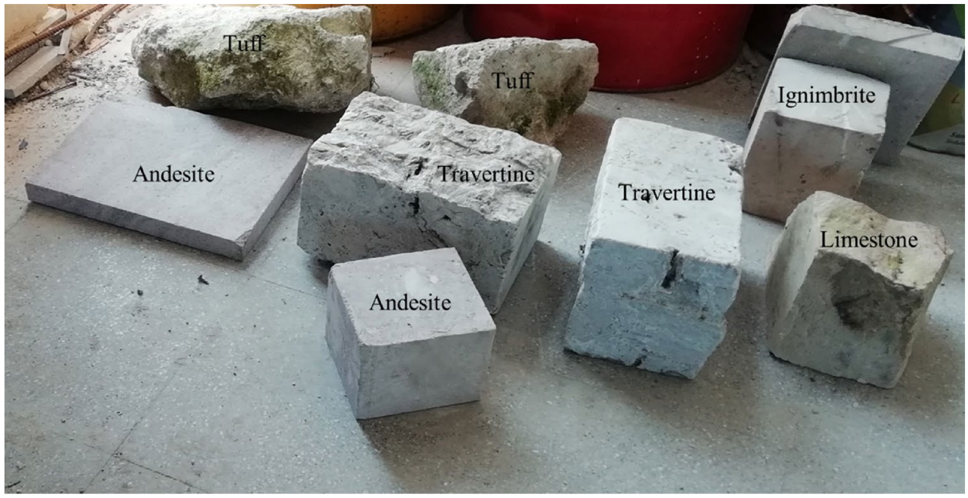


Fig. 1 Rock types used in experimental studies

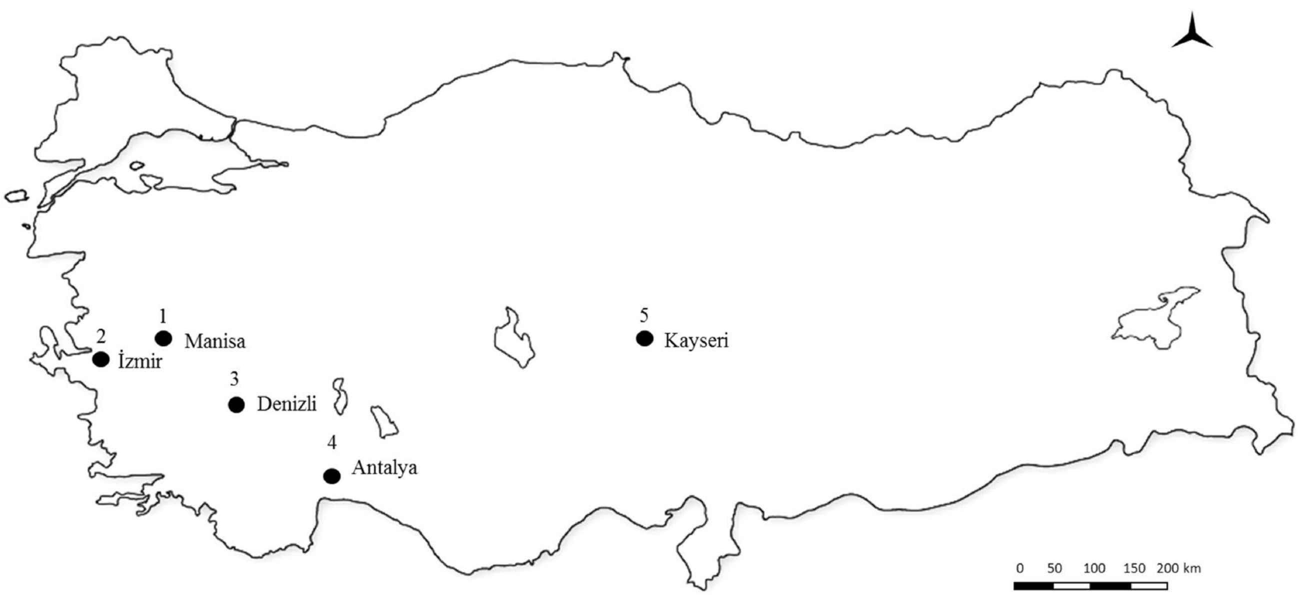


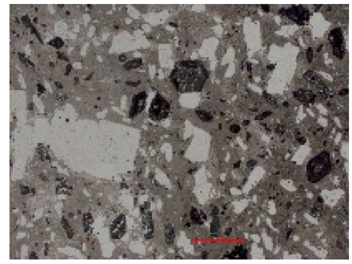
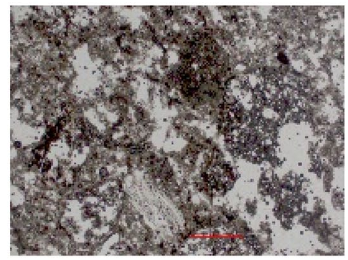
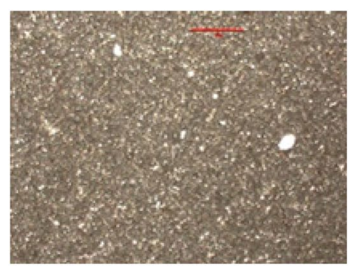
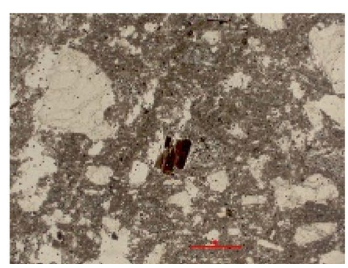
Fig. 2 Distribution of sampling locations

Experimental studies

In accordance with the aim of this study, some physical and geomechanical experiments (Mode I and Mode II fracture toughness, Schmidt hammer, Brazilian tensile strength, porosity and unit weight tests) were carried out in this study. Brazilian tensile strength and fracture toughness tests were performed on rock discs with 54.7 and 100 mm diameters, respectively, as suggested by ISRM (2007). Geomechanical tests were conducted under dry and fully saturated conditions. The rock samples were saturated with drilling muds using a vacuum saturation equipment (Fig. 4) as suggested by ISRM (2007). So the vacuum saturation at least 1 h was used to create a fully saturation of test samples. Drilling fluids used for saturation with bentonite and polymer additives prepared by considering the API Specification 13A (2010). Liquid solution of hydrolyzed polyacrylamide/polyacrylate copolymer and sodium bentonite (Baroid 2016) were used as additives of drilling fluids. The content of the drilling fluids used in this study is given in Table 3.

Mode I fracture toughness values of rock types tested in this study were obtained using cracked chevron notched Brazilian disc (CCNBD) specimens as expressed by ISRM (2007). 20 s time duration was used for fracture toughness tests from loading application to failure occurrence as suggested by ISRM (2007). Mode II fracture toughness values of tested rocks were also determined using central cracked circular disk (CCCD) specimens. This method has already

Table 1 Petrographical name, sampling location and micrographs of tested rock samples

Name of rock (Sample no)	Sampling location	Micrograph of rock samples
Andesite (1)	Manisa	
Tuff (2)	İzmir	
Travertine (3)	Denizli	
Limestone (4)	Antalya	
Ignimbrite (5)	Kayseri	

been used by a number of investigators (Awaji and Sato 1978; Shetty et al. 1987; Liu et al. 1998; Fowell and Xu, 1994; Al-Shayea et al., 2000; Chen et al. 2001; Yang et al. 1997; Dong, 2008). The preparation of CCCD sample is easy and the mode mixities (from mode I to mode II) can be obtained by selecting the loading angle and relative crack length (Dong et al. 2008).

Final chevron notch crack length (a_1) for CCNBD tests and the half length of crack (a) for CCCD tests were selected as 35 mm. In this study, CCCD tests were conducted by considering the methodology proposed by Dong (2008) and

Table 2 Mineral contents of tested rocks

Rock type	Mineral Content (%)				
	Clay	Cristobalite	Quartz	Feldspar	Calcite
Travertine	–	46.7	–	–	53.3
Tuff	38.1	53.1	0.9	3.1	4.8
Ignimbrite	30.2	56.2	2.4	5.6	5.6
Andesite	31.3	50.5	0.8	17.4	–
Limestone	–	21.7	2.8	–	75.5

Dong et al. (2004). Dong et al. (2004) and Dong (2008) stated that mode II stress intensity factor can be obtained using the following expressions for central cracked circular disk (CCCD) which is exposed to diametric compressive force.

$$K_{\mathrm{II}} = \sigma\sqrt{\pi a}F_{\mathrm{II}} = \frac{P}{\pi BR}\sqrt{\pi a}F_{II} = \frac{P}{B\sqrt{\pi R}}\sqrt{\alpha}F_{II} \quad (5)$$

$$F_{\mathrm{II}} = 2\sum_{i=1}^{n} A_{2i}f_{2i}\alpha^{2(i-1)} \quad (6)$$

where B is thickness and R is radius of the disk, α is relative crack length, a is half length of crack, F_{II} is the normalized stress intensity factor.

Dong (2008) also stressed that pure mode II test condition can be obtained by selecting a critical loading angle value (θ_c) which refers to angle between loading direction and initial crack and is dependent to relative crack length (α). In this study, the critical loading angle value of 16.96° was used in CCCD tests as suggested by Dong et al. (2004)

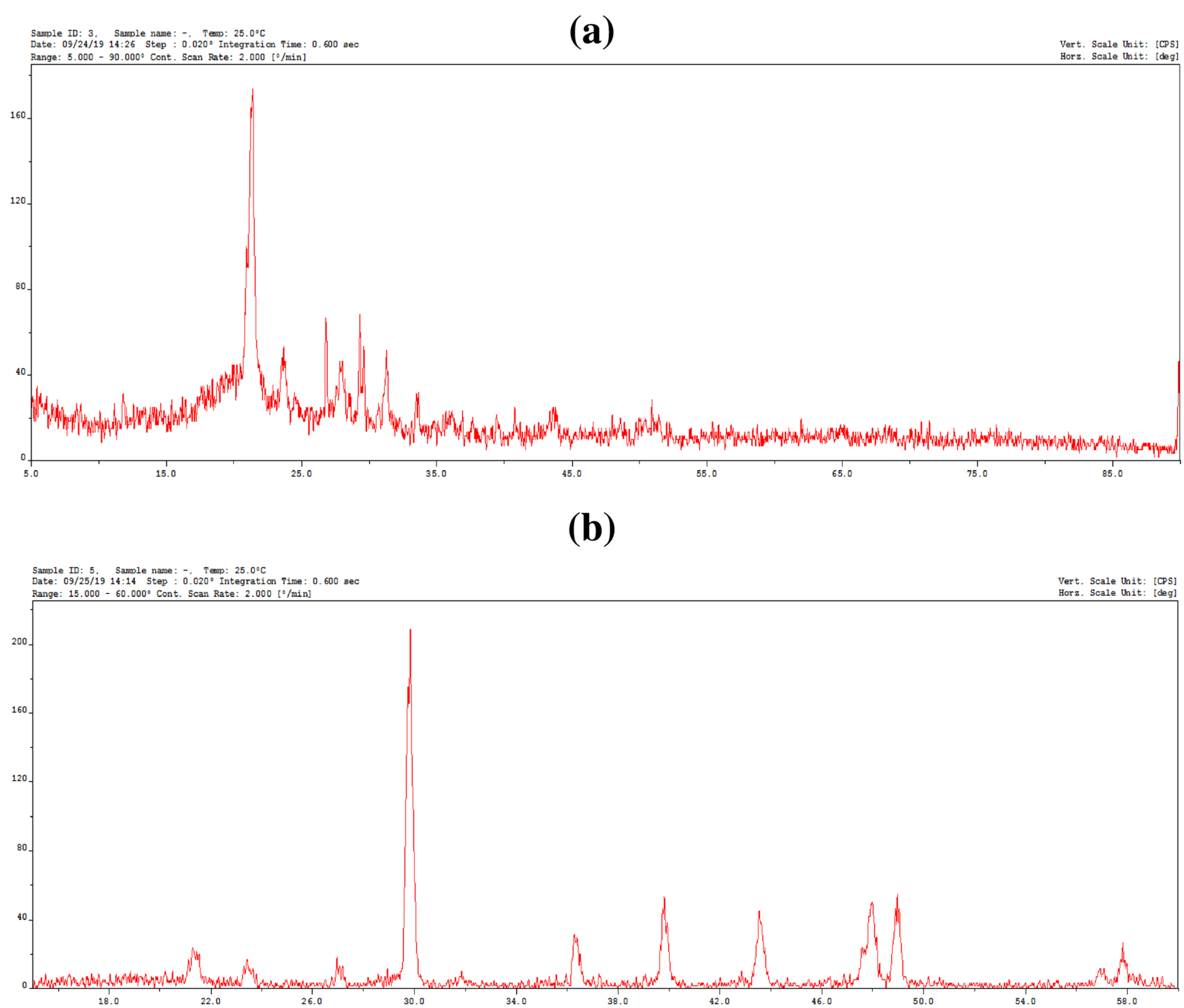


Fig. 3 X-ray diffractograms of **a** Ignimbrite and **b** limestone

Fig. 4 Vacuum saturation equipment

Table 3 Content of drilling fluids

Content of drilling fluid	Type of drilling fluid	
	Bentonite-based drilling fluid (g/l)	Polymer-based drilling fluid (g/l)
Bentonite	25	25
Polymer	–	8
NaOH	1	1

and Dong (2008). Dimensionless parameters of FI and FII (dimensionless parameters) for tested Brazilian disk samples were found as 1.85 and 2.46, respectively. An overview to disk specimens before and after fracture toughness tests and schematic illustrations of CCNBD and CCCD test specimens are given in Fig. 5 and 6, respectively.. In this study, a total of 170 tests (84 for Mode I and Mode II fracture toughness tests, 46 for Brazilian tensile strength tests, 5 for Schmidt hammer test, 25 for unit weight tests, 10 for porosity tests) were carried out. The physical and geomechanical properties of tested rocks determined by experiments conducted in this study are given in Table 4. The typical test specimen and failure patterns obtained by fracture toughness tests are presented in Fig. 6.

Results and discussions

The saturation effect on variation of fracture toughness

As stressed in Sect. 1, there are few studies with limited scope on the vulnerability of fracture toughness of rocks to saturation, and there are no investigations about drilling fluid effects on fracture toughness. The experimentally proven adverse effects (increment in pores and size and quantity of microcracks and weakening of adhesive forces) determined by Hua et al. (2019) and the corresponding decrement of fracture toughness values, make it necessary to investigate this topic in detail. In other words, the invasion of drilling fluids around the borehole walls for different engineering applications makes it necessary to take into account fracture toughness values under saturated conditions. For this purpose, in addition to the dry situation, two different saturated conditions by drilling fluids with bentonite and polymer additives were used in the experiments. By considering the test results given in Table 4, the dry situation gave the highest fracture toughness values and there was a decrement on geomechanical properties of rocks (both for fracture toughness values and Brazilian tensile strength values) as a result of saturation. However, the decrement varies depending on the type of drilling mud used in the experiments and the geomechanical properties studied (Fig. 7).

While the values of geomechanical properties (Brazilian tensile strength, Mode I and Mode II fracture toughness) obtained as a result of the saturation by drilling fluids with polymer additive were close to those determined in dry condition, saturation with drilling fluids with bentonite additive led to high reductions in those values. The highest decrement ratios obtained for fracture toughness values due to saturation by drilling fluids with bentonite additives are 57.14% for ignimbrite and 45.90% for limestone, respectively (Fig. 8).

So it is clear that Mode I and Mode II fracture toughness values were halved for some rock types. However, these reduction rates were reduced to 45.71% and 34.43%, respectively, when the drilling fluids with polymer additives were used. In addition, the difference between fracture toughness values obtained in dry conditions and those determined in saturated conditions with drilling fluids with polymer additives were almost zero for travertine and andesite units. All in all, while the average reduction rates were 21.10% and 16.50% in saturated conditions by drilling fluids with polymer additives for K_{IC} and K_{IIC}, respectively, these rates increased to 36.45% and 35.77% as a result of saturation with drilling fluid with bentonite. Therefore, it is quite obvious that the polymer is an additive having the property of preventing high levels of reduction in fracture toughness values of rocks under saturation. It can be also understood from the experimental results found by Roy et al. (2017a) that decrement percentages of fracture toughness values due to water saturation are close the values found in this study for saturation by bentonite-based fluids.

As stated by Grillet et al. (2012) and Zosel (1985), gel structure of polymer and adhesive bond developed across the boundary between gel and solid surface are the main reasons

Fig. 5 An overview to disc samples before and after fracture toughness tests

why higher resistance is valid to applied loads. So the generation and propagation of crack surfaces across the rock materials needs more work when the rock pores are filled by drilling fluids with additive of polymer. On the other hand, higher viscosity value of drilling fluid with polymer additive than of water creates higher excessive pore pressures which means variations on fracture toughness values due to saturation by drilling fluids with high viscosity values.

K_{IC}/K_{IIC} ratios obtained in this study were also presented in Fig. 9. The average value of K_{IC}/K_{IIC} ratios is around 0.6. However this value is changed due to variation of rock type and saturation state. Low values means that the value of increment in resistance due to replacement of polymer fluid instead of air is greater than decrement in resistance due to adverse effects stressed by Hua et al. (2019). This situation is especially valid for limestone and Ignimbrite units.

Before starting to hydraulic fracturing, saturated condition, which were created by invasion of drilling fluids into geological formations around the wellbore, may exist and the mechanical and fracture-mechanical parameters are varied at different degrees due to composition of drilling fluids. Therefore, fracture toughness, which represents the in-situ condition (under drilling fluid saturation), should be considered for a succesfull hydraulic fracturing simulation. So the type and properties of drilling fluids are very important for a successful hydraulic fracturing design. This study gives a general comparison between fracture toughness values of five different rock types measured under different saturation conditions (dry, saturated by bentonite-based drilling mud and saturated by polymer-based drilling mud) and helps to engineers about proper drilling fluid selection.

Results of statistical analyses and soft computing models

Results of simple regression analyses

To date, the relationship between fracture properties (Mode I and Mode II fracture toughness) and tensile strength has been examined in numerous studies as stressed above. As emphasised by Zhang (2002), the failures obtained by tensile, compressive and shear strength tests essentially results from tensile microcracks developed by stresses applied in corresponding tests. Zhang (2002) also stressed that formation of fractured surfaces due to extension of cracks is similar for both tensile strength and fracture toughness tests. Therefore, these two parameters are mechanically related. On the other hand, Bazant and Pfeiffer (1986) stressed that shear fractures can be generated due to formation of a zone of preformed inclined tensile microcracks which are partial and discontinuous. Then these microcracks connect by shearing (Bažant and Pfeiffer 1986). Lockner (2015) stated

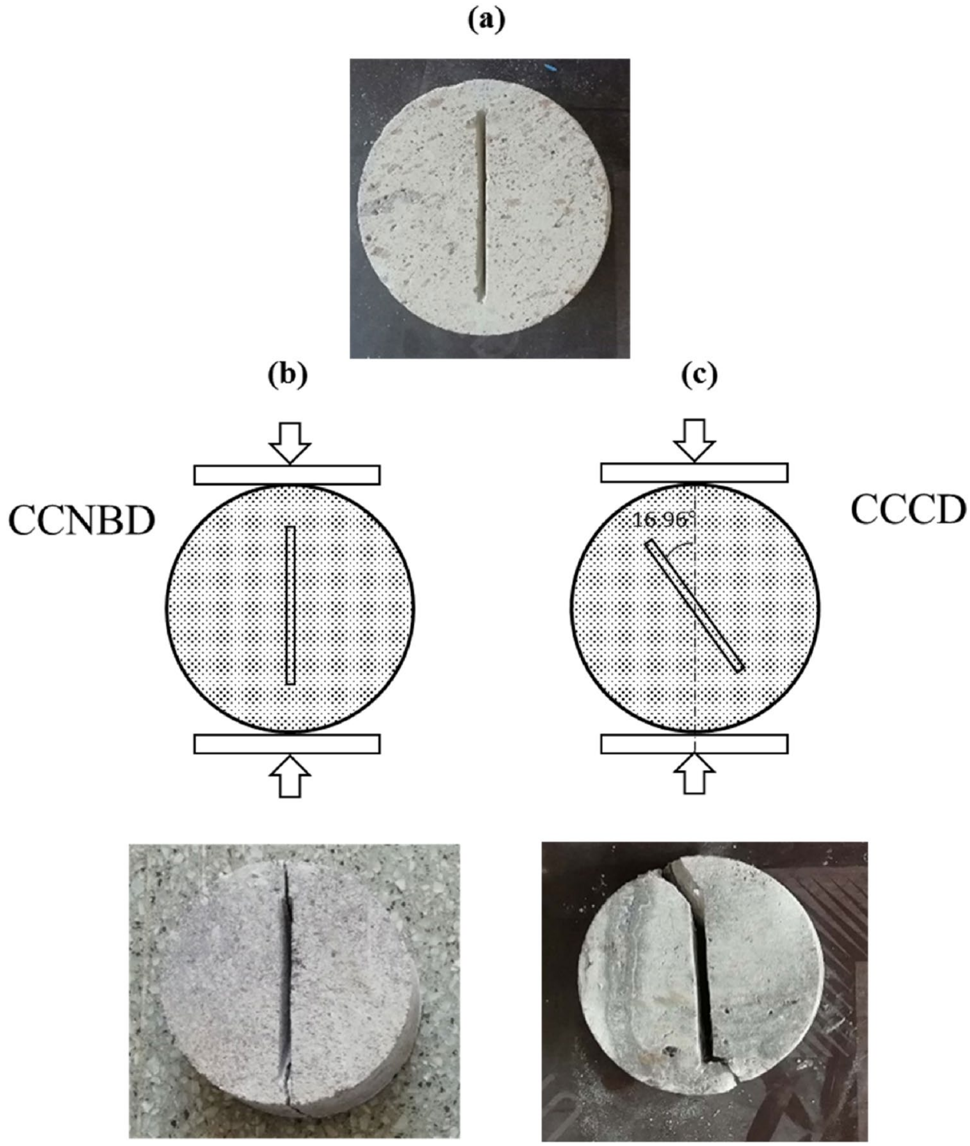


Fig. 6 **a** Typical disc specimen **b** loading conditions and failure patterns obtained in this study for CCNBD and **c** CCCD tests

Table 4 The physical and geomechanical properties of tested rocks

Rock Type	Mechanical and Physical Parameters											
	Mode I Fracture Toughness, K_{IC} (MPa $m^{0,5}$)			Mode II Fracture Toughness, K_{IIC} (MPa $m^{0,5}$)			Brazilian Tensile Strength, σ_t (MPa)			Schmidt rebound value, N	Unit Weight, γ (kN/m^3)	Porosity, n (%)
	Drilling Fluid Type											
	Dry	Polymer	Bentonite	Dry	Polymer	Bentonite	Dry	Polymer	Bentonite	Dry	Dry	
Travertine	1.11	1.07	0.8	1.83	1.75	1.31	2.56	2.45	2.08	46.50	24.19	2.85
Limestone	0.42	0.24	0.20	0.61	0.40	0.33	2.52	2.15	1.48	43.20	21.62	11.36
Ignimbrite	0.35	0.19	0.15	0.53	0.48	0.32	1.80	1.69	1.53	31.20	15.40	25.22
Tuff	0.16	0.13	0.12	0.24	0.19	0.15	0.91	0.61	0.61	15.67	13.75	23.15
Andesite	1.11	1.17	0.89	2.26	1.95	1.64	4.31	4.21	3.80	55.40	24.81	4.16

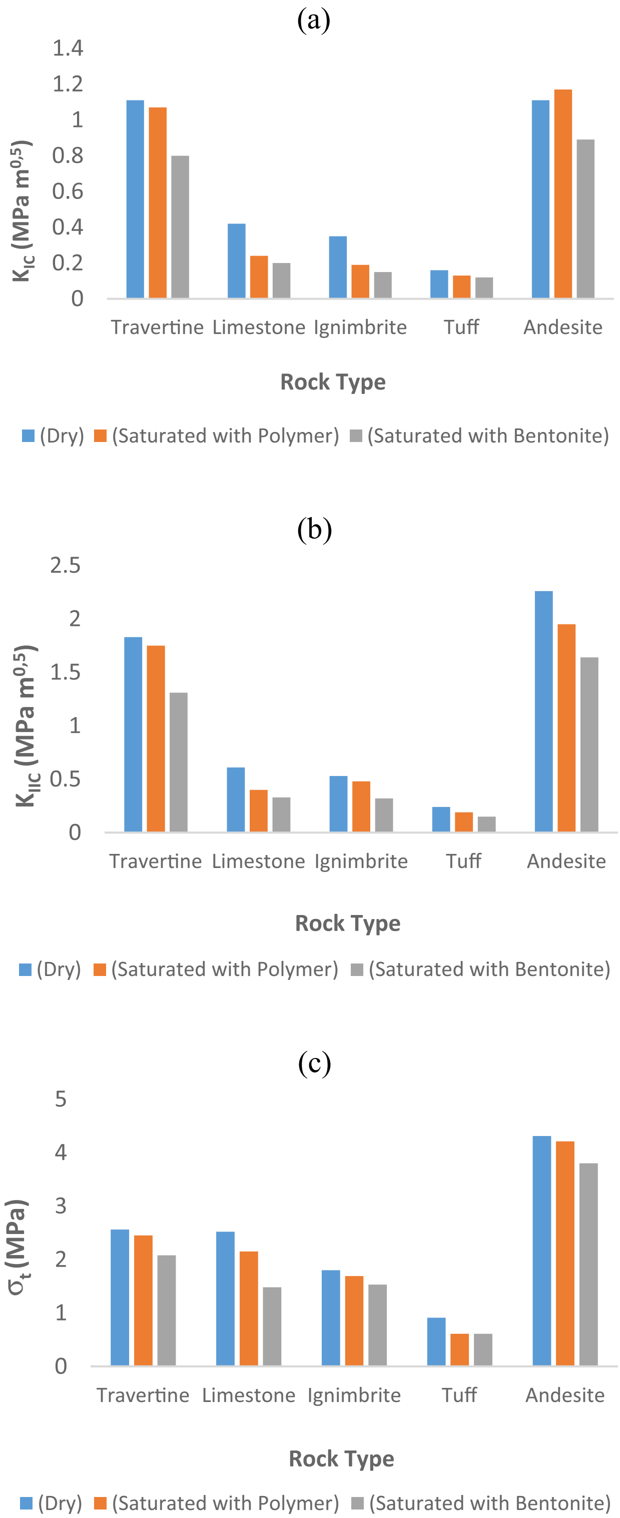


Fig. 7 Variation in **a** Mode I fracture toughness **b** Mode II fracture toughness and **c** Tensile strength due to saturation.

that local stresses generated near a fracture point which is loaded in shear involve both shear and tensile component and this will cause to local tensile type failure before fracture toughness for failure in shear is obtained. So it can be inferred that both K_{IC} and K_{IIC} are related to tensile strength of rocks. Therefore, in addition to investigation of drilling fluid effects on fracture toughness values, the prediction of K_{IC} and K_{IIC} from tensile strength was examined by simple regression analyses. In these analyses, the average test results obtained for three different situations (dry, saturated by drilling fluids with bentonite or polymer additives) were considered. As it is clear from Fig. 10, the relationship of overall trends derived by simple regression analyses was determined (Fig. 10a, b) and the corresponding equations are given in Eqs. 7 and 8. It is clear that the coefficients of determination of equations derived by simple regression analyses are moderate, and the relationships include a certain level of prediction error. However these prediction errors means that the drilling fluid effect on fracture toughness parameter should be evaluated using another parameter. So there is a requirement to perform a multivariate regression analysis which can consider a few independent variables.

$$K_{IC} = 0.1074e^{0.5922\sigma_t} R^2 = 0.69 \tag{7}$$

$$K_{IIC} = 0.1351e^{0{,}7386\sigma_t} R^2 = 0.70 \tag{8}$$

where K_{IC} is the Mode I fracture toughness (MPa $m^{0.5}$), K_{IIC} is Mode II fracture toughness (MPa $m^{0.5}$) and σ_t is tensile strength (MPa).

Roy et al. (2017b) also investigated the relationships between strength properties and fracture toughness values of different rock types. The authors derived linear relationships and compared with the relationships obtained by previous studies. Roy et al. (2017b) also mentioned about the limitation of relationships and stated that there is a major limitation of these linear relationships for especially lower values.

So, in this study, to overcome to this limitation, which is based on the linear approach conducted by simple regression analysis, multivariate regression analysis and a soft computing method were also used to predict the fracture toughness values of rocks.

Results of multivariate regression analyses

The adverse effect of saturation on mechanical properties of rocks was described using Effective Clay Content (ECC) which is suggested by Karakul and Ulusay (2013) by considering the experimental data from 14 different rock types, including such as andesite, limestone, tuff, ignimbrite, sandstone and marl. There were rock types with zero or low clay content values among these rocks.

It is a parameter that considers both porosity and clay content of rock materials and the defines the level of negative effect of saturation on mechanical properties of rock materials. In addition to this, the authors found that ECC is inversely proportional to the strength properties determined

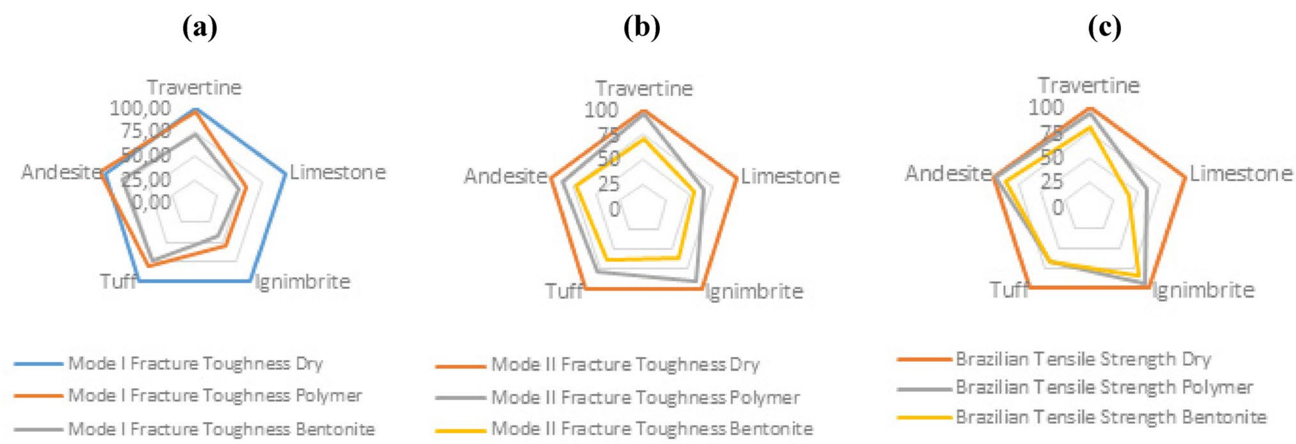


Fig. 8 Variation in geomechanical parameters of rocks as a percentage obtained due to saturation in **a** Mode I fracture toughness, **b** Mode II fracture toughness and **c** Tensile strength determined under dry condition

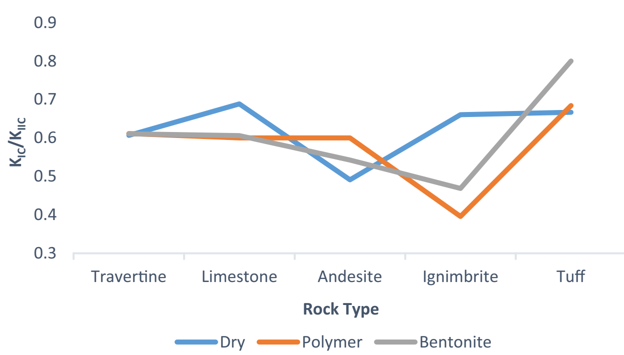


Fig. 9 The ratio of *K*IC/*K*IIC for different rock types

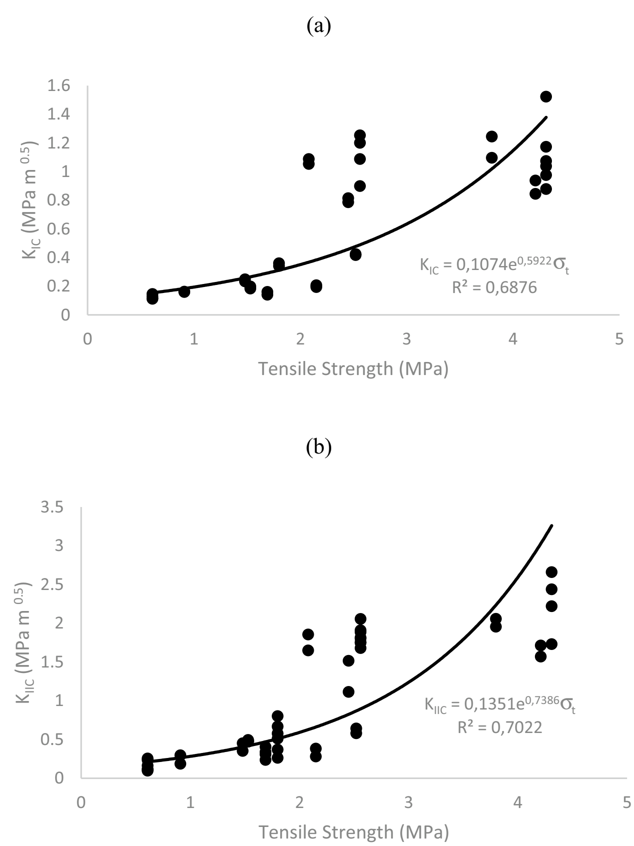


Fig. 10 The relationships between **a** Mode I fracture toughness and tensile strength **b** Mode II fracture toughness and tensile strength

under dry conditions. Karakul and Ulusay (2013) also derived an equation by which the ECC parameter was determined from ΔV_p ($V_{psaturated}$–V_{pdry}). So, in addition to tensile strength, the variation of fracture toughness values of rock materials due to saturation by different drilling fluids was also linked to ECC parameter (or ΔV_p) in the multivariate regression analyses and ANFIS modelling.

Because of the existence of two independent variables linked to fracture toughness, multivariate regression analyses were also carried out in this study. Linear relationships between the dependent and independent variables (K_{IC} and K_{IIC}) were derived using multivariate regression analyses. The multivariate relationships derived by multivariate regression analyses can be seen from Eqs. 9 and 10. Because of the existence of two different independent variables used in the multivariate regression analyses, the multivariate equations derived have higher coefficients of determination than the coefficients of simple regression equations. The planes corresponding to multivariate equations are presented as a 3D scatter plot of the statistical data in Fig. 11. It is obvious from Fig. 11 that the distribution of test data plots follows the fitted plane. The reliability of regression coefficients derived by multivariate regression analyses was also examined by F-test and the results are given in Tables 5 and 6. As can be understood from the tables, the significance values are lower than the critical value of $p = 0.05$ and so the equations created by multivariate

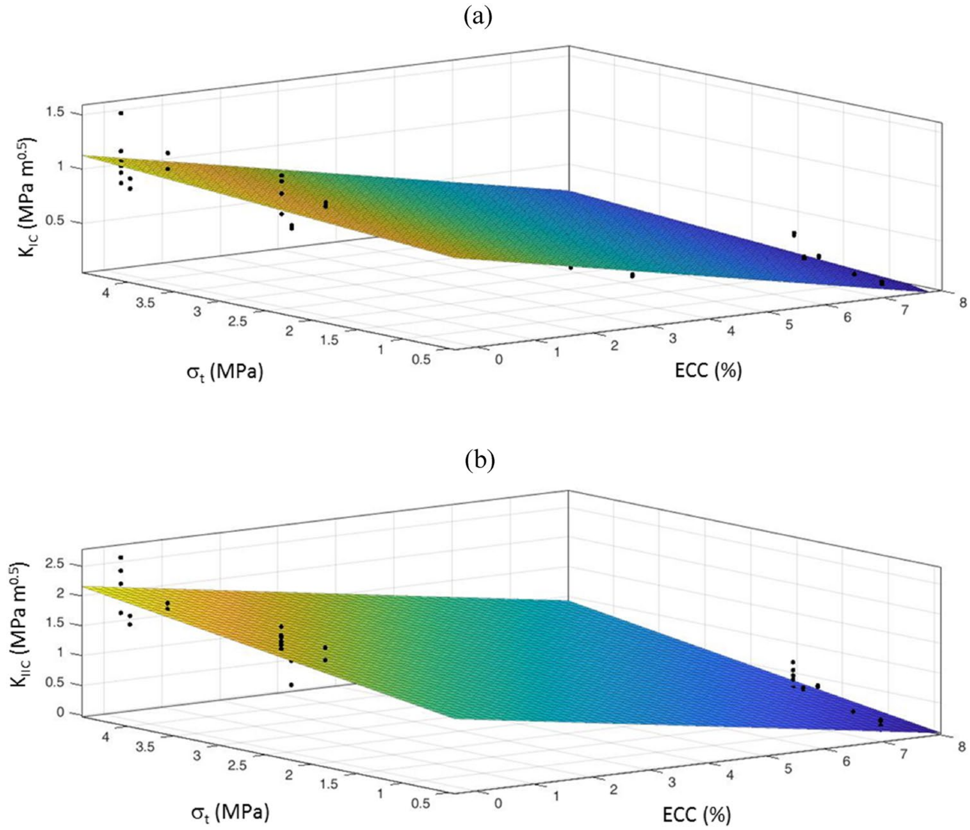


Fig. 11. 3D scatter plot for multivariate predicton equations of **a** K_IC and **b** KIIC

Table 5 F-test statistics for Eq. 13

Regression Statistics-K_{IC}	Degree of freedom (df)	Sum of squares (SS)	Mean square	*F*	Significance (P)
Regression	2	6,026,732	3,013,366	98,4928	1.22E-14
Residual	33	1,009,628	0,030,595		
Total	35	7,036,359			

Table 6 F-test statistics for Eq. 14

Regression statistics-K_{IIC}	Degree of freedom (df)	Sum of squares (SS)	Mean square	*F*	Significance (P)
Regression	2	24,95,429	12,47,714	157,9658	4.52E-21
Residual	45	3,554,387	0,078,986		
Total	47	28,50,868			

regression analyses are statistically reliable. So it is possible to predict the K_{IC} and K_{IIC} with derived multivariate equations using tensile strength and ECC (or ΔV_p) (Table 7). However it should be also noted that the linear approach conducted by multivariate regression analyses produce considerable errors especially for high tensile strength values.

$$K_{IC} = 0.8272 - 0.1039\text{ECC} + 0.057759\sigma_t \quad R^2 = 0.86 \quad (9)$$

Table 7 The prediction performances of multivariate regression analyses and ANFIS models

Model	Predicted parameter	RMSE	MAPE
ANFIS	K_{IC}	0.33	19.12
	K_{IIC}	0.41	25.69
Multiple Regression	K_{IC}	1.00	30.52
	K_{IIC}	1.89	34.61

$$K_{IIC} = 1.078708 - 0.1466\text{ECC} + 0.228046\sigma_t \quad R^2 = 0.88 \tag{10}$$

where K_{IC} is the Mode I fracture toughness (MPa $m^{0.5}$), K_{IIC} is Mode II fracture toughness (MPa $m^{0.5}$), ECC (%) is efective clay content value and σ_t is tensile strength (MPa).

Besides multivariate regression analysis performed using ECC and tensile strength as independent variables, the multivariate regression analyses were also conducted by considering the porosity and tensile strength values as independent variables. As a result of this analysis, the multivariate equations were obtained which are given in Eq. 11 and 12. However the determination coefficients for these equations are lower than Eq. 9 and 10.

$$K_{IC} = 0.5248 - 0.0241n(\%) + 0.1546\sigma_t \quad R^2 = 0.83 \tag{11}$$

$$K_{IIC} = 0.5998 - 0.0334n(\%) + 0.3571\sigma_t \quad R^2 = 0.84 \tag{12}$$

Because ECC includes both porosity and clay content components and both of clay content and porosity have adverse effect on mechanical properties, the prediction quality of Eq. 9 and 10 determined as higher than Eq. 10 and 11.

Results of neuro-fuzzy analysis

A soft computing method (ANFIS) was used to perform an estimation of fracture toughness parameters (K_{IC} and K_{IIC}). ECC and tensile strength parameters were used as input parameters, Mode I and Mode II fracture toughness values were considered as output parameters. ANFIS modelling was created using Matlab software. Grid partitioning method was used to create initial Fuzzy Inference System. Generalized bell membership function was used in the analyses. The membership function parameters were modified using hybrid optimization technique. The structure of model was presented in Fig. 12.

To compare the prediction quality of multivariate regression and ANFIS model, statistical parameters of mean absolute percentage error (MAPE) and root mean square error (RMSE) were used (Table 9). As it can be understood from Table 9, the values of RMSE and MAPE were calculated higher for multivariate regression analyses than the values determined for ANFIS model. So the prediction capability of ANFIS model is higher than the prediction performance of multivariate regression analysis.

The surfaces created by ANFIS modelling is given in Fig. 13. As it can be understood from Fig. 13, while fracture toughness parameter (both K_{IC} and K_{IIC}) is directly proportional with tensile strength, ECC is inversely proportional with fracture toughness parameters. However the derived relationships is not in the linear form and the orientation of fitted surface is highly changeable so the ANFIS model gives better prediction performance than the prediction capability of multivariate regression analysis.

Roy et al. (2018) also conducted a study which include prediction of mode-I fracture toughness from mechanical properties for dry rocks using multiple regression analysis, fuzzy inference system, adaptive neuro-fuzzy inference system and artificial neural network. The authors emphasized that soft computing method (especially ANFIS) have higher prediction capability than conventional methods.

Conclusions

The aim of this study was to investigate the vulnerability of fracture properties of rocks to saturation created with drilling fluids with different compositions and to derive relationships between fracture toughness values and tensile strength. The investigation of drilling fluid effect on fracture toughness values of different rock types is a novelty for this study because there is no comprehensive study conducted on the topic. By consideration of the geomechanical test results,

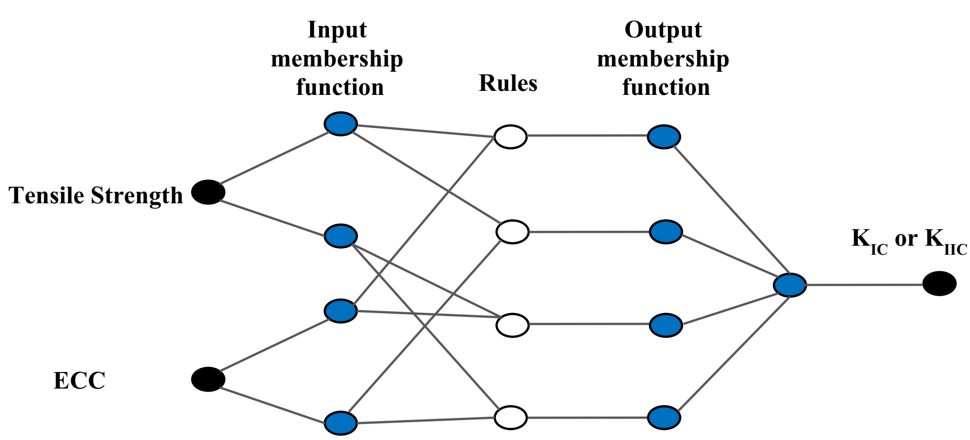


Fig. 12 The structure of ANFIS

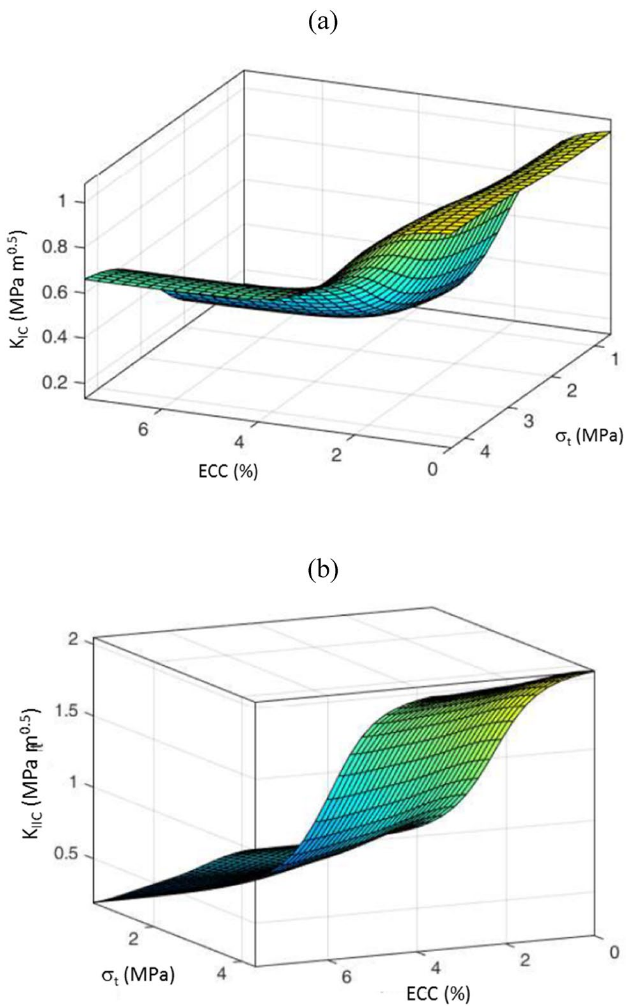


Fig. 13 Surface plots obtained by ANFIS modelling performed for prediction of (**a**) KIC and (**b**) KIIC, respectively

statistical evaluations and soft computing models, it is indicated that the saturation created by drilling fluids reduces the fracture toughness values, and there is a statistically significant relationship between fracture toughness values and two independent variables (tensile strength and ECC (or ΔV_p) of rocks. The main conclusions of this study are given below.

The geomechanical tests showed that the saturation with drilling fluids creates a decreasing trend which is valid for both fracture toughness and Brazilian tensile strength values of rocks. However, the chemical composition of drilling fluids has a considerable effect on the level of this decrement. The addition of polymer, instead of bentonite, in drilling fluids prevents the dramatic decrease in fracture toughness and Brazilian tensile strength values of rocks. In addition to high viscosity value, gel structure of drilling fluid with polymer additives creates high resistance across the boundary between solid particles and pores of saturated rocks. So the drilling fluid with polymer additive is much more favorable in terms of borehole stability than the drilling fluid with bentonite additive.

Simple and multivariate regression analyses were carried out to estimate the fracture toughness values from the tensile strength of rocks. The relationships created as a result of simple regression analyses produced moderate coefficients of determination with a certain level of prediction error. To create stronger relationships, multivariate regression analyses were used, and in addition to tensile strength, the Effective Clay Content (or ΔV_p) was also used as an independent variable. The prediction efforts created by multivariate regression analyses produced equations with strong coefficients of determination. The reliability of the multivariate equations was examined by *F*-test, and the equations were determined to be statistically significant. In addition, a soft computing method (ANFIS) was used to estimate the fracture toughness parameters and very high prediction performance was obtained using this method. It should be also noted that the low number of data used in regression analyses and soft computing method can be expressed as a limitation.

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Declarations

Conflict of ınterest The author declares that he has no conflict of interest.

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