

Evaluation of rock mechanical properties via scratch testing and its impact on energy production: comprehensive review

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Abstract The scratch test is a non-destructive method made up of pushing a tool across the surface of a weaker rock at a given penetration depth. The uniaxial rock strength (UCS), fracture toughness (K_{IC}), and other geomechanical parameters influences how fracture nucleates, but fracture sizes and geometry adopted in hydraulic fracture design and modeling are most often overestimated. Although several researchers have attempted to evaluate UCS, K_{IC} and other geomechanical properties in conventional and unconventional formations through scratch testing method, but there remain differing opinions on the fundamental approach and principles to be adopted in estimating those properties. Therefore, the evaluation of geomechanical parameters and their effect on hydrocarbon exploration, energy storage, and hydrocarbon exploitation remain an important issue for energy industry. In this paper, we present a comprehensive review of the methods of approach, applications, and the mechanics of rock scratching. We show the merits of scratch test over other methods of estimating rock mechanical properties. Our review focuses on over 50 previous experimental studies using scratch tests in the past few decades to investigate UCS, K_{IC} and other geomechanical properties, including their impact on rock failure, fracture initiation and propagation. Finally, we highlight the fundamental research questions that are yet to be addressed. We envisage that advancement in our knowledge will improve optimization of hydrocarbon exploitation, energy storage, and field-scale modeling for energy production operations.

1. Introduction

The scratch test is a quasi-non-destructive method made up of pushing a tool across the surface of a weaker rock and tracing the groove at a given penetration depth. The uniaxial rock strength (UCS) which is the ultimate stress a rock can withstand before undergoing failure, is characterized by rock confining pressure, stress-strain relationship, and pore-fluid pressure. Analysis and prediction of the in-situ rock failure behavior as a function of rock type, pore pressure, spatio-temporal stresses, and fault-reactivation potential provides critical information for proactive decision-making to achieve successful energy production operations. In the optimization of hydrocarbon exploitation, hydraulic fracturing has proven to be one of the most efficient methods [1, 2]. During this treatment, complex fracture networks are often generated, and the interaction of hydraulic and natural fractures significantly influences the

complexity of the fracture networks created [3, 4]. Stronger rocks will exhibit greater fracture toughness (K_{IC}), which will influence the fracture geometry and propagation. UCS, K_{IC} , and other rock mechanical parameters influencing how the fracture nucleates [5], fracture size and geometry, but fracture sizes and geometry adopted in hydraulic fracture design and modelling, Discrete Fracture Network (DFN) modeling, and Finite Element Modeling (FEM); are most often overestimated. Although scratch tests are applicable nowadays to several fields of science and engineering, ranging from strength characterization of rocks and cements/ceramics [6, 7, 8, 9, 10, 11, 12], to damage of polymers [13, 14, 15, 16, 17, 18, 19, 20, 21] and metals [22, 23, 24, 25], and quality control of thin films and coatings [16, 19]; the underlying rock failure mechanisms, characterization, and applications has not been fully explored. Although several researchers have attempted to evaluate and quantify UCS, fracture toughness, and other rock

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mechanical properties in conventional and unconventional reservoir rocks using indentation and scratch testing methods, but there remain differing opinions on the fundamental approach and principles to be adopted in estimating those parameters.

In this paper, we discussed and summarized the key findings regarding the use of scratch testing method to estimate rock strength and other geomechanical properties over the past few decades. We extensively discussed the methodology, modifications, and applications of scratch test approach and devices published research studies. We highlighted the advantages of scratch testing method over other conventional methods of estimating geomechanical properties. We further provided recommendations for future research to address the identified outstanding problems related the use of scratch test method to estimate geomechanical properties for improved hydrocarbon exploitation and production.

2. The Scratch Test Method

2.1. Scratch Test Method Vs Other Methods

The uniaxial compressive test using load frame to evaluate the UCS of core plugs is one of the most popular methods. The indentation test method is another popular conventional method of estimating mechanical properties of rocks [26], and other materials. This method involves the use of a scratching tool to create indentations on the surface of the material surface. In a research study [27], micro-nano indentation method was utilized to evaluate and predict K_{IC} in shale rocks, but the study failed to account for maximum holding stage on the indentation-displacement curves in fracture toughness estimation. This fracture toughness model deficiency was highlighted and corrected in [28], but the final K_{IC} values are in the order of magnitude two. The macroscopic and mesoscopic rock mechanical parameters of shale rocks were investigated by authors in [29] using micro-indentation test method. The shale outcrops from the Cambrian Longmaxi formation in Sichuan Basin, China, was utilized for the study. In the results, the authors observed that mesoscopic elastic modulus and indentation hardness are heterogeneously distributed across the formation and exhibits a non-linear increase behavior with rise in packing density. The microscopic mechanical properties of shale rocks were not accounted for in this study. The shale rock samples from the Longmaxi formation in Sichuan Basin, China, was utilized to estimate K_{IC} through micro-indentation method [30]. The authors aim to address the previous limitation of the K_{IC} estimation

in [28], and their results showed much lower K_{IC} values. In K_{IC} measurement using indentation method, results are more of qualitative, and can yield high inaccuracy and subjectivity by virtue of the crack length measurement requiring optical imaging method, which is onerous task for non-translucent rocks like shale [31]. Other method of estimating rock's UCS are the point-load test [32, 33]. The "Drill Test" [34] was developed using the drilling concept and incorporates 2/3 butt core sections to evaluate UCS in shale rocks.

The rebound hardness test method using Equotip^R hardness tester [35, 36] was initially adopted for evaluating the UCS of rocks, but recently utilized for creating UCS logs and strength contrast profiles of shale rocks [37, 38]. The rebound hardness test can also be carried out using Schmidt hammer [39]. Although the rebound index test is also useful in qualitatively estimating the UCS of rocks, it has proven inefficient in providing a continuous and accurate quantitative rock strength profile [40]. This is another means the scratch test has proven its efficiency over other methods of testing rock strength by providing continuous high-resolution logs of rock strength with high degree of repeatability. The effect of anisotropy in K_{IC} was estimated in [41] using Chevron Bend (CB) test and Boundary Element Method model. The authors in [42] also utilized the Chevron Notched Semicircular Bend (CNSCB) test to estimate rock strength and fracture toughness of Woodford shale rocks, with the estimated fracture toughness (K_{IC}) values in Lower and Middle Woodford shale much lesser than values of Upper Woodford shale. In study [43] using a modified Short-Rod sample geometry to estimate anisotropic K_{IC} values of Mancos Shale rock, conflicting values were obtained in divider, short-transverse, and arrester configurations. Coring operation was also suggested [44] as another viable method of estimating UCS from data obtained from acoustic and bulk density logs.

The advantages of scratch test method over other conventional methods discussed to estimate rock strength and other geomechanical properties are that [45, 46, 47, 48, 49, 50, 51]:

- a. It is quasi non-destructive, and the post-test core samples remain intact which can be utilized for other destructive or non-destructive tests.
- b. It provides direct equivalent measurement with the rock's UCS.
- c. It requires limited and minimal level of sample preparation.
- d. It is simple, quick, and highly repeatable.
- e. It can be conducted on any dimension of rock, as the results are not affected by the core sample geometry.

- f. It provides precise continuous profile of rock strength over the scratch interval.

The scratch profile from the scratch tests provides a reliable quantitative measurement of the scale and distribution of the heterogenous properties along the tested core samples.

2.2. The Mechanics of Rock Scratching

In the scratch testing method, continuous trace of the groove of the rock surface is conducted with a stronger cutting tool, while the cutter penetration depth (d) and the velocity (v) between the cutter and the rock are held constant. The horizontal force (F_T) is parallel to the cutter velocity, and the vertical force (F_V) which is normal to the cutter velocity; are measured. The rock cutting configuration is also characterized other parameters such as: the back-rake angle (θ); the cutter/probe geometry; the contact surface between the cutter and the rock surface which is represented by l ; the friction coefficient (μ) beneath the wear flat of the cutter. The mechanisms of rock scratching are evident in the linear relationship between cutter penetration depth (d) and F_T . The two rock failure mechanisms depending on the cutter penetration depths are [46, 52]:

- a. Ductile failure mode: Also known as "plastic flow". The ductile failure mode occurring at shallow penetration depth (d), is characterized by the rock shearing ahead of the cutter. As the rock matrix and the grains are dislodged, the rock grains and powder accumulate continuously ahead of the cutter, and they are removed by the moving cutter.
- b. Brittle failure mode also known as "chipping", The brittle failure mode occurring at large penetration depth (d), is characterized by macroscopic fractures generating from the tip of the cutting tool and propagates upwards towards the rock surface ahead of the cutter. The chips and fragments formed are removed by the cutter.

[Break]
 The brittle failure mode is dependent on fracture toughness (K_{IC}), the ductile failure mode on UCS, and the transition between ductile and brittle failure modes is dependent on the cutter penetration depth (d). Researchers [53] adopted the Bazant's Size Effect Law (SEL) to investigate the critical ductile-to-brittle transition depth in a wide range rock type. This critical ductile-to-brittle transition penetration depth (d_c), distinguishes the ductile failure regime from the brittle failure regime. The Quasi-brittle fracture property of cement paste was investigated by [5] to account for the linear elastic relationship between applied forces and scratch width and depth

($w\sqrt{d}$). The authors proposed a linear scaling method from scratch geometrical scale to large scale ranges for estimating K_{IC} in homogenous materials.

2.3. Scratch Test Devices

2.3.1. The Rock Strength Device

The Rock Strength Device (RSD) [45, 46, 47, 49, 54, 55, 56, 57, 58] is designed to scratch the rock surface while the normal and tangential forces applied to the cutter are measured, and the device is kinematically controlled. The main components of the RSD are: 1 - a transverse with a core holder of length l ; 2 - a moving cart; 3 - housing the vertical positioning system; 4 - the load cell; 5 - cutting tool; 6 - computer controlled stepper-motor (controls the horizontal movement of the cart); 7 - horizontal ball screw; 8 - gearbox; 9 - the vertical positioning system (controls the depth of cut); 10 - micrometer; 11 - locking system (keeping the vertical mechanical system locked against the frame to maintain a constant penetration depth). The load sensor measures tangential (F_T) and vertical (F_V) forces acting on the cutter.

2.3.2. The Wombat Machine

The wombat scratch test machine [50, 51, 59] as shown in Fig. 1, is a unique scratch test equipment developed by Epslog S.A. with the capability of testing core samples up to 3ft long and a diameter range of 0.5 in. to 6 in. The following are the main components of the Wombat machine: horizontal bed on which the core samples are fixed; mobile carriage to hoist the vertically erected cutter; load sensor measuring F_T and F_V ; high-definition camera to capture continuous images of the rock core surface during scratching. The results are processed and analyzed by a computer software solution.

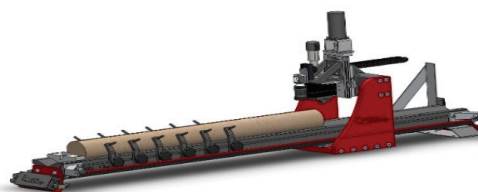


Figure 1: Wombat scratch machine (Image courtesy of Epslog S.A.[59])

2.3.3. Others

The Mechanical Profiler Test System (MPTS) from TerraTek TSI™ [60, 61, 62] is another type of scratch test equipment utilized for estimating rock

mechanical properties and other parameters through the scratch testing method. Its system consists of a moving cart containing a core sample holder, a cutting tool with the rock “scratching” capability, loading cell to measure the vertical and horizontal forces acting on the rock surface. As part of an existing compression machine, a simple scratching cell was developed [63] and utilized to create rock strength correlation for predicting UCS of rocks in Saudi Arabia. Most recently, the miniature linear cutting device [64] was developed using a milling machine and designing it to measure forces and distance scratched by the probe.

3. Estimation of Rock Mechanical Properties using Scratch Test Approach

3.1. Uniaxial Compressive Strength (UCS)

The scratch test can be resourceful in estimating reservoir geomechanical and petrophysical properties. The concept of obtaining rock strength information from rock cutting tests was proposed [54], and this approach was dependent on phenomeno-logical model of continuously cutting of rock with blunt cutter. This cutter/rock interaction model in ductile failure mode was developed based on three assumptions, irrespective of the cutting tool wear. These assumptions are that [54, 65]: (i) the forces acting on the cutter face, averaged over a distance higher than the penetration depth, is directly proportional to the cross-sectional area (A_c) due to horizontal force; (ii) the inclination of the average force acting normal to the cutter face is constant; (iii) friction force at the wear-flat rock interface exists. The above developed model is composed of three major parameters:

- a. the intrinsic specific energy (ε) applicable to the rock cutting process;
- b. the inclination (ζ) of the average force acting on the face of the cutter;
- c. the coefficient of friction (μ) on the wear flat/rock interface.

The model assumptions and its application to estimate rock strength is summarized in Eqns. 1-6 as:

$$F_T = \varepsilon(1 - \mu\zeta)wd + F_V \quad (1)$$

$$\mu = \tan \phi \quad (2)$$

$$E = E_o + \mu S \quad (3)$$

$$E = \frac{F_T}{wd} \quad (4)$$

$$S = \frac{F_V}{wd} \quad (5)$$

$$E_o = \varepsilon(1 - \mu\zeta) \quad (6)$$

The feasibility of RSD to estimate rock strength parameters from scratching test was first conducted in [54]. The researchers used blunt and sharp cutters in conducting the scratch tests on sandstone samples. The RSD was utilized [46] to investigate to estimate the rock strength of different rocks using scratch test method. The experiment was conducted on 130 quarry rocks and 236 oil and gas reservoir rocks (sandstones, limestones, dolomites and shales). The results of the tests show strong correlation between the values of intrinsic specific energy (ε) and the UCS. Another study [52] on 35 different sandstone samples and 24 different carbonate samples was conducted to assess the strength and Young’s modulus (stiffness) of sedimentary rocks through scratch testing. The values of intrinsic specific energy (ε) obtained in their results agree with the UCS, which further validates the efficiency of scratch test for quick and effective estimation of UCS and other geomechanical properties in rocks.

Thin layer of weakness or heterogeneity along rock core can be captured through scratch testing, and this was showed [48] in the rock strength estimation experiment conducted using the RSD. The UCS results [66] from the uniaxial lab test and the scratch test from Brazilian limestone core with high heterogeneity was presented by researchers. Their results validated the use of scratch testing to estimate UCS and Young’s modulus in rocks such as limestone.

Authors [67] combined the strength profiles with well logs to create correlations of strength and other petrophysical properties such as porosity, density, and sonic velocity. The continuous strength profile obtained provides a reliable quantitative measurement of the scale and distribution of the heterogenous properties along the tested core samples. The mechanistic basis of equivalence between a rock’s estimated intrinsic specific energy (ε) and the UCS was further validated by a research conducted using the scratch test. In the authors’ results, they observed in sedimentary rocks that in addition to the compressive strength, the Mohr-Coulomb failure envelope could also be obtained by scratch testing by the substitution of the scratching tool or cutter in order to evaluate the rock friction coefficient. The UCS of carbonate rocks was estimated by conducting 85 uniaxial compressive tests with RSD, and the result range from 9.16 MPa to 401.83 MPa [56]. The authors in [54] attempted to investigate the rock strength under the ductile-failure mode, and the K_{IC} under the under brittle-failure mode through scratch testing method. The authors applied the Bažant’s Size Effect Law (SEL) to the

experimental results to estimate K_{IC} and UCS of different rock types. The fracture toughness values are estimated in brittle regime, while the UCS is estimated in ductile regime.

Some researchers attempted to investigate the mechanical properties of 4 different rocks (limestone, coal, conglomerate, siltstone) using scratch tests with various scratch probes [68]. In their results, they observed high degree of agreement between the values average normal force and the compressive and tensile strengths of the rocks tested. They showed that the UCS and Brazilian tensile strength (BTS) of the 4 different rock samples can be estimated by averaging the forces acting on the cutter in the scratch test. The authors also suggested that the rock properties can be best estimated at cutter penetration depth > 0.4 mm. The results from the study can be used for borehole probe design for evaluation of rock strength in small hole drilled for bolting or blasting.

The rock material and rock material strength have been mostly mis-interpreted to be equal to intact rock and intact rock strength [69]. This misconception was properly defined [70, 71] where intact rocks are rocks that are free from fractures and contains minimal disturbance by the core sampling process; whereas intact rock strength is the UCS of intact rock conducted in core samples of ~ 0.2 ft in diameter. The successive tests conducted [72] proposed that a rock's principal stresses relationship at failure are characterized by two parameters, the uniaxial compressive strength and an instant rock strength parameter. The author suggested those parameters could be estimated in rocks by unconfined compression test and the Brazilian indirect tension test.

3.2. Fracture Toughness

Fracture toughness (K_{IC}) is a measure of a material's resistance to fracture propagation. Propagating fractures tends to travel along the path of lowest resistance, but the fracture orientation, direction and limit of its path creates a complex relationship between in-situ stress-field, the rock's anisotropic mechanical properties, and the pore pressure, and fracturing pressure [43]. Reliable geomechanical values such as K_{IC} , are of utmost importance in hydraulic fracturing design and simulation to achieve successful operation and optimum hydrocarbon recovery. Notwithstanding the several attempts by researchers to investigate the elastoplastic behavior of shale rocks, its fracture characterization has not been adequately investigated. It is a common knowledge that fractures is inherently a multi-scale phenomenon, but a substantial number of studies have limited fractures to the macroscopic sphere. The

novel study by [31] was focused on fracture characterization in gas shales using the scratch test method. The authors used shale rocks from 3 systems: Torcian Shale in Paris, Basin, France, and Lower and Upper Woodford shale in Oklahoma, USA. The authors presented a novel method of estimating fracture energy and K_{IC} in shale rocks at microscopic scale through the scratch testing method. An experiment involving four consecutive tests with an Anton Paar scratch testing machine was utilized for this study using a sphero-conical scratch probe.

The authors presented a scratch force linear relationship for scratch probes with axisymmetric shapes [11]. In the force-scaling relationship developed, the scratch probe geometries considered are conical probe, flat punch, and hemi-spherical probe. The scratch force criterion utilized for characterizing scratch resistance of materials is termed as the scratch hardness (H_T) [75], and it can be quantified in Eqn. (5) as:

$$F_T \stackrel{\text{def}}{=} H_T A_c \quad (5)$$

The authors [74] addressed the limitation of study [6] in accounting for cutter blade width in estimation of K_{IC} . The force-scaling relationship for scratch probe geometries are well defined [7, 11] in Eqn. (6) for conical scratch probe, and in Eqn. (7) for spherical scratch probe:

$$F_{eq} = \sqrt{F_T^2 + \frac{3}{5} F_V^2} \quad (6)$$

$$F_{eq} = \sqrt{F_T^2 + \frac{665}{1188} F_V^2} \quad (7)$$

For the crack-initiation point, authors in [31] used threshold criterion for the energy release rate (G); that the fracture propagation occurs when $G = G_f$. Where G_f , is the fracture energy and is the threshold value. Their scratch fracture toughness (K_s) estimation is given as:

$$K_s = \frac{F_T}{\sqrt{2pA_c}} \quad (8)$$

The scratch toughness of shale rock in Eqn. (1) is highly dependent on scratch orientation, while the probe function, $2pA_c$ is dependent on the stylus geometry and the penetration depth, d . The term $2pA_c$ is applicable for scratch testing using flat punch, spherical, and conical or sphero-conical scratch probe geometries. Since a sphero-conical probe was utilized, the expression for the probe function was given as:

$$2pA_c = \frac{4 \tan \theta}{\cos \theta d^3} \quad (9)$$

The authors also attempted to estimate G_f for an anisotropic material such as shale rock, using the J-

integral solution [75, 76]. The fracture energy (G_f) for anisotropic rocks such as shale is given as:

$$G_f = \frac{1-\nu_{ab}^2}{E_a} K_s^2 \quad (10)$$

where E_a , is the Young's modulus parallel to the bedding plane, while ν_{ab} , is the Poisson's ratio parallel to the bedding plane.

From their results, the authors observed that increase in penetration depth d yields higher fracture toughness (K_s) and focalize at an asymptotic value (K_s^∞) which highlights the ductile-to-brittle transition as a function of depth of penetration. The microscopic scratch toughness estimated was observed to be to three times greater than the macroscopic fracture toughness estimated through other methods, while the microscopic fracture energy is twice as much as that estimated by other researchers at macroscopic scale. The scanning electron microscopy (SEM) result shows very rough scratch surfaces which tends to result in deflection of the fracture, due to the interaction between the shale rock's weaker component such as clay, and much stronger constituents such as quartz. The fracture mechanical behavior observed by the authors from the SEM images are: (i) particle pull-out; (ii) fracture bridging; and (iii) fracture branching, micro-fracturing, and fracture trapping.

In a microscale experimental study [77], fracture mechanical behavior was investigated to characterize its initiation and propagation in shale and sandstone rocks using microscale mechanical scratch tests.

The K_{IC} and fracture directionality were evaluated in the formation to identify the effect of grain-scale heterogeneity and inelasticity on hydraulic fracturing design and operations. Micro-scratch testing was conducted on the shale and sandstone cores used in the experiment and the cores are sourced from the Monterey formation. The continuity of core scratching increases the degree of elastic and plastic deformation of the rock. In F_T vs. scratch length results for sandstone and shale, the instantaneous change in penetration depth along the scratch length signifies fracture occurrences.

In cores oriented along the bedding plane in shale rocks, K_{IC} values intersect at an average value with increase in scratch length, and this is similar to the asymptotic value (K_s^∞) in [31]. The authors [77] combined Acoustic Emission (AE) with SEM to observe the scratch area, and the damage within and outside the scratch path, to characterize the crack surface events. The fracture mechanical behavior in sandstone and shale rock samples includes fracture branching, fracture bridging, particle pull-out, and fracture deflection. This validates the shale fracture mechanical behavior presented in [31].

3.3. Other Parameters

Scratch testing was utilized in sanding prediction evaluation by obtaining the vertical distribution of the rock's mechanical properties [60]. The logging measurements (GR, Sonic, porosity, and density) of the mechanical properties was obtained experimentally using the TerraTek TSI™ scratch machine. The tests conducted on 85 ft sandstone reservoir provided reliable results showing the capability of the scratch testing to (i) evaluate the vertical heterogeneity of the core; (ii) choose a number that is representative of the core sections for rock mechanical experiments; (iii) displaying the minimum vertical resolution display and log evaluation; (iv) provide quick and immediate calibration of logs for proactive decision to prevent wellbore instability and sand production.

Micro-scratch test can be resourceful in evaluating mudrock brittleness of shale rocks [78]. The results showed that the transverse force measured can be used to estimate rock brittleness index. The impact of scratching speed, loading rate and diamond probe radius on the critical load for scratch tests was conducted on coatings of diamond indenter [24]. Scratch testing also proved resourceful in studying the effect of bit wear in polycrystalline diamond compact (PDC) bits [79]. UCS from scratch test can be combined with sedimentology, core analysis and wireline logs to provide better characterization of rock's heterogeneity and create continuous profile of the geomechanical properties in un-cored intervals [80].

Borehole instability issues arising from oil and gas drilling operations can be addressed by predicting the strength of homogenous and heterogenous rocks using scratch test [63]. This test was conducted on 13 carbonate and sandstone rocks with the scratching cell. Researchers [61] utilized the scratch testing method to evaluate continuous rock drillability by correlating the scratch test's intrinsic specific energy and the micro-drilling tests with PDC bits. In their results, the drillability of heterogenous sandstone from Songnan oilfield, China, was determined using combination of scratch and micro-drill tests. Filter cakes formed by various mud systems was addressed using scratch test method to determine the rock strength and stiffness and correlated them to external filter cake probing. In the research results [81] conducted on sandstone samples, the scratch test tool showed the entire shear strength profile starting from the mud/cake interface to the cake/rock boundary. The authors also showed the capability of the scratch testing tool to clean-out mud filter cake layers to a lowly thickness of 0.1 mm.

4. Conclusions and recommendations

In this paper, we provided an up-to-date review the use of scratch testing method to estimate rock strength and other geomechanical properties over the past few decades. Subsequently, we presented the comparison of scratch testing method to other conventional methods. We further highlighted the methodology, modifications, and applications of the scratch test and its devices published research studies. The advantages of scratch test method over other conventional methods in estimating rock strength and other geomechanical properties are that:

- a. It is quasi non-destructive, and the post-test core samples remain intact which can be utilized for other destructive or non-destructive tests.
- b. It provides direct equivalent measurement with the rock's UCS.
- c. It requires limited and minimal level of sample preparation.
- d. It is simple, quick, and highly repeatable.
- e. It can be conducted on any dimension of rock, as the results are not affected by the core sample geometry.
- f. It provides precise continuous profile of rock strength over the scratch interval.

In our statistical analysis of papers reviewed, the scratch test utilization for estimating rock strength is 56%, other parameters is 33%, and fracture toughness is 11%. This shows there is minimal study on fracture toughness estimation in rocks using scratch test method.

Based on outstanding issues for studies of UCS, K_{IC} , and other geomechanical properties, we propose the following recommendations for further research to improve optimization of hydrocarbon exploitation, energy storage, and field-scale modeling for energy production operations.:

- a. Extended study of rock fracture characterization at a microscopic scale.
- b. Further study on the heterogenous microstructure and composition of rocks with a high-level accuracy.
- c. Achieving a rock surface roughness with a lower maximum penetration depth over an extended surface area.

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