



Fracture Toughness of Rocks and its Use in Drill Bit Selection

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Abstract

Understanding of rocks such as compressive strength, tensile strength, or fracture toughness is essential for proper drill bit selection. However, due to time constraints and limited funds only unconfined compressive strength (UCS) is measured directly or evaluated indirectly from log data. This greatly oversimplifies bit choice, especially in hard rocks.

The present work confirms that compressive strength is about 5-10 times greater than the tensile strength and the ratio of compressive to tensile strength is much more in stronger rock than compared to weaker rocks. Further, the fracture toughness is found to be inversely proportional to the tensile strength. This suggests that the rock breakage would be efficient in compression or shear mode in weaker rocks as against direct or indirect tensile fracture mode in harder rocks. The former is typical in PDC bit application, whereas, the latter is typical in roller cone bit applications.

Introduction

Drilling is essential in civil, mining, and petroleum industries. Furthermore, it's a pre-requisite in exploration and exploitation of oil, gas, and other energy resources. The cost of drilling constitutes a major component in all of the above. For example, the cost of drilling oil in US alone in 1997 was \$ 16.4 billion [1]. Further, with the depletion of shallow energy resources the cost of drilling is getting increasingly higher; especially, when harder rock formations are encountered and where higher rate of penetration is desired. Therefore, in order to minimize the cost of drilling it is important that the conditions for optimum performance of drilling are identified.

The optimum performance of drilling depends on large number of factors; most importantly rock type, bit type, rock-bit interactions, hydraulics, stability, and its compatibility. Over the past decades a significant advancement has taken place in understanding of these subjects. As a result, rock formation of any type and any strength can be drilled, at least technologically, by any drill bit type. However, in order to reduce of cost of drilling further, it is important to enhance the knowledge of most poorly understood subject, that is rock and its interaction with the drill bit as compared to other factors.

The poor understanding of rock and its interaction with bit is because it's an interdisciplinary subject. It needs some expertise in the field of geology of rock formation, chemistry of minerals and its bond structure, physics of force or energy application, rock mechanics aspects of deformation process, and fracture mechanics aspects of failure process.

Moreover, it is difficult, sometime impossible, to mimic the actual drilling process in rocks taking place in the original environments of boreholes. Thus, any additional work on rock and its interactions with drill bit will further enhance the understanding of optimum performance of bit. However, this subject falls beyond the scope of the present work. The following work focuses only on the strength and fracture toughness of rocks and its interaction under different drill bit types.

Strength of Rock

Strength of rocks is characterized in terms of compressive, shear, or tensile depending upon the mode of load applications. These are measured directly as in unconfined compressive strength (UCS) and tensile strength, or indirectly as in shear strength using the well known Mohr-Coulomb failure envelope resulting from tri-axial strength testing data. Figure 1a and 1b show typical shape of samples and loading mechanism for compressive and tensile strengths; whereas, Figure 1c shows typical tri-axial testing setup for calculating shear strength. A typical Mohr-Coulomb failure envelope is shown in Figure 2. This is a composite diagram, which shows compressive, shear, and tensile strengths at unconfined condition or at various confining pressures. The slope of the line, also called internal friction angle, is typically constant, especially for weaker or medium strength rocks. In such cases, a combination of UCS and Tensile strength, UCS and friction angle, or compressive strengths at two confining pressures are sufficient to describe the full spectrum of strengths.

The UCS is the most commonly and easily measurable parameter. The relevance of this, in rock drilling processes, is well understood. Further, a large number of works has taken place in correlating UCS together with friction angle with measurable log data [2, 3]. Further, because of time constraints, limited budget and

easiness of testing procedure, rocks is evaluated either based on log data or on UCS values. This greatly oversimplifies the full strength spectrum, especially in hard rocks. Therefore, it is important to thoroughly investigate the rock characteristics including other fundamental properties like fracture toughness.

Fracture Toughness, K_{IC}

Strength of rocks or ability to carry loads or resist deformation in presence of a dominant crack or void is fracture toughness. This is a powerful tool which describes when, where and why fracture takes place. This depends on the crack size and its sharpness (leading to the stress concentration effects), the stress level applied, and the material property i.e. fractures toughness [4]. The fracture toughness may also be expressed in terms of crack opening, shearing along the crack plane, and tearing away from the crack front (may be considered similar to tensile, compressive or shear strength); however, fracture toughness in crack opening mode (K_{IC}) has been used mostly to explain fracturing by direct or indirect tension. The unit of K_{IC} is denoted in terms of $MPa\ m^{1/2}$, $MN/m^{1.5}$, or $psi/in^{1/2}$.

Measurement of fracture toughness is a relatively new procedure compared to UCS, tensile, or shear strength by tri-axial tests. However, it has been observed that the fracture toughness values of rocks are an order of magnitude lower than that for metals. For example, the fracture toughness of iron is $\sim 120 MPa\ m^{1/2}$ and the same for the rocks is as much as $\sim 2 MPa\ m^{1/2}$. The low value of fracture toughness in rocks is due to the low level of plasticity at the crack tip, which in turn is due to their brittleness. The same is reflected in their respective measured tensile strength also.

The typical methodology to measure fracture toughness of rock as suggested by International Society of Rock Mechanics (ISRM) [5] is shown in Figure 3. A cylindrical core sample with a precise calibrated chevron notch at the center is loaded under three points bending to break apart at the central chevron notch. The load at failure is used to calculate the K_{IC} . The measured values of fracture toughness for wide variety of rock types together with their measured values of compressive and tensile strengths following standard procedure have been described and discussed elsewhere [6]. The data is compiled and analyzed here in terms of rock breakage by compressive or shear failure as in PDC bit or by indirect tensile fracture mode as in roller cone bits.

Rock Tested

Eight different rock types ranging from homogenous and isotropic to anisotropic rocks were selected for the tests. The rock types covered a wide range of mineralogy, texture, and homogeneity. The isotropic rocks consisted of two types of relatively fine-grained granites (Stanstead

granite, A and Barre granite, B). The anisotropic rock types consisted of a gneissic granite, C and marble, D from the north-eastern region of Quebec; Kingston Limestone, E, and Vineland limestone, F, from eastern region of Ontario, a gneissic rock, G from Hemlo gold mine area of Ontario, and Quartz, H from Baskatong region of Quebec [6]. Table 1 shows the identification of the rock types and their standard physical properties.

Table 1: Physical properties of rocks being tested [4].

Rock Identification	Density (g/cc)	Porosity (%)	P wave (m/s)	S wave (m/s)
A-Stanstead Granite	2.68	0.60	4170	2670
B-Barre Granite	2.63	0.69	4250	2715
C-Gneissic Granite	2.75	0.78	3750	2370
D-Marble	2.72	0.25	4650	3077
E-Kingston Limestone	2.71	0.18	5340	2900
F-Vineland Limestone	2.64	2.33	4665	2880
G-Gneiss	2.78	0.68	4770	3080
H-Quartz	2.63	0.21	4420	2600

Results

The results obtained for both compressive as well as tensile strength varied in a wide range depending upon the inherent structure of the rock samples and its orientation with respect to direction of loading. This was expected as the core samples drilled from rock were not consistent with respect to plane of weakness, especially in limestone and gneissic rocks. This resulted in larger than normal data scatter, but it was in keeping with the intention of obtaining 'global' properties rather than along any specific direction. The wide variation could have been compensated by large number of tests (8 to 12 sample tested in this case), which was not practical. Nevertheless, the compressive strength was found to be about 5-10 times greater than the tensile strength of corresponding rocks in a wide variety of rock types. This confirms to the earlier work [7, 8].

Figure 4 shows the trend for the ratio of compressive strength to tensile strength together with their compressive strength on two axes. It can be seen that the ratio of compressive to tensile strength is much more in stronger rock than compared to weaker rocks.

The measured value of fracture toughness varied within a close range except in case of gneissic marble. The large scatter in the latter case was because many times the fracture did not start from the tip of the calibrated notch, thus the resulting toughness values were rejected. The higher toughness values are characteristic of more non-linear or ductile failure associated with large

number of crack generation. Low toughness means fast and brittle failure with almost negligible non-linear work.

Further, the fracture toughness, K_{IC} , is found to be inversely proportional to the tensile strength, Figure 5. This suggests that the stronger rocks can easily be broken down under crack propagation mode.

Bit Selection Based on K_{IC}

Drill bits are essentially of two kinds, roller cone and PDC (earlier, it was known as drag bits) bits. The basic difference between roller cone (RC) and PDC bit is that RC crushes the rock under direct influence of weight on bit (WOB) involving compression underneath the tooth and/or indirect tension in the vicinity thereby generating extensive damage and chips near bit-rock interface. The latter, on the other hand cuts the rock under shear mode under the influence of horizontal force (a component of Torque on Bit) [9, 10]. Figure 6 shows these two concepts schematically. It should be noted that there is another style of diamond bit and used in very hard rocks, where breakage is by abrasion or friction; however, this has been left out of discussion as the present work focuses mainly on bit selection when rock failure is by compression, tensile or shear forces.

Since their introduction to the field in 1975, PDC bits have revolutionized medium hard rock drilling. Historically, PDC bits can effectively drill rocks with shear strength about 5 times lesser than the compressive strength, see Table 2 below. However, it should be noted that the tensile strength of rocks are about 10 times lesser than compressive strength. This is concluded from both the present work (Figure 4) as well as previous work [7, 8]. Table 2 shows the compressive strength, Tensile strength, and shear strength together with their ratios for various rock types [7]. Further, since fracture toughness, K_{IC} is shown to be inversely proportional with tensile strength (Figure 5), rocks of lower K_{IC} values (higher tensile strength or for that matter higher compressive strength) will have the tendency to fail much earlier than waiting to exceed its shear or compressive strengths.

Table 2: Typical Compressive, Tensile, and Shear Strengths of common rocks [7]

Rock Types	Compressive Strength, σ_c (psi)	Tensile Strength, σ_t (psi)	Shear Strength, C_0 (psi)	σ_c / σ_t	σ_c / C_0
Granite	25,375	2,320	4,640	11	5
Diabase	32,625	3,625	6,163	9	5
Slate	21,750	1,958	3,263	11	7
Quartzite	32,625	2,900	5,800	11	6
Sandstone	13,775	2,103	3,480	7	4
Shale	7,613	870	2,393	9	3
Limestone	20,300	2,175	4,350	9	5

Therefore, roller cone bits in which direct and or indirect tensile forces are more predominant than shear forces, should be preferred over PDC bits when high compressive strength (conversely high tensile strength and thus low K_{IC}) rocks are encountered.

Discussion

The present work is based on fracture toughness and compressive- and tensile-strength values resulting from atmospheric test conditions. Under confined conditions, intuitively, it is expected that strength values would increase while overcoming the extra confining pressures. However, no data is available to prove (or disprove) this hypothesis. The subsequent paragraph discusses some of the understanding on these strength values measured under confined conditions.

Compressive strength is known to increase under confining pressures, and its increase can be seen in a typical Mohr-Coulomb failure envelope. However, often a sudden decrease in load carrying capacity, especially in low porosity hard rocks [11] indicates low tensile strength and/or fracture toughness even under confinement.

Fracture toughness has been measured under confinement in the past, albeit with limited success. Some of the preliminary work indicates that the K_{IC} increases proportionately as compared to compressive strength. However, rate of increase of K_{IC} is much lower in hard rocks than compared to weaker rocks [12]. Further, fracture toughness in mode-II, K_{IIIC} (failure in shear mode) increases much more in hard rocks than compared to weaker rocks [13]. Thus, K_{IIIC}/K_{IC} (this may be considered as ratio of compressive strength to tensile strength in our discussion) also indicated stronger rocks to fail more easily in crack opening mode than compared to crack shearing mode even under confinement.

Finally, the concept of tensile strength under confinement is relatively new. Jonathan and Frederick, 2004 [14] have shown the effect of confinement on tensile strength by using a completely different approach using a tri-axial extension of notch-cut dog-bone rock samples. The results are inconclusive. Future work in this direction will greatly help define the role of confining pressure on tensile strength.

Conclusions

Strength of rocks is one of the most critical considerations in a drill bit selection. Strengths of rocks are characterized in terms of compressive, shear, or tensile depending upon the mode of load applications. Ideally, the measured value of one indicates the value of others for a given failure envelope. Further, the strength of a rock in presence of a dominant crack or void is fracture toughness. These rock properties, duly

measured by suggested standard procedures, are essential for a proper choice of a drill bit. However, many times, due to the limited time, budget, and simplicity of the testing procedure, only unconfined compressive strength is measured directly or evaluated indirectly from log data. This greatly oversimplifies the choice of bit, especially in hard rocks.

The present work compiles the measured values of compressive and tensile strengths of a wide variety of rock types together with their measured values of fracture toughness. Further, the data is analyzed in terms of rock breakage by compressive or shear failure as in PDC bit or by indirect tensile fracture mode as in roller cone bits.

The compressive strength is found to be about 5-10 times greater than the tensile strength of corresponding rocks in a wide variety of rock types with their strengths varying in a wide range. This confirms the earlier work also. However, the ratio of compressive to tensile strength is much more in stronger rock than compared to weaker rocks. Further, the fracture toughness is found to be inversely proportional to the tensile strength. This suggests that the stronger rocks can easily be broken down under crack propagation mode.

Based on these findings it can be suggested that the compressive strength as well as tensile strength data is equally important, especially in hard rock drilling applications. Further, the rock breakage would be efficient in compression or shear mode in weaker rocks as against in direct or indirect tensile fracture mode in harder rocks. The former is typical in PDC bit application, whereas, the latter is typical in roller cone bit applications.

Future works

A potential use of this work is in hard rock drilling. A thorough investigation of target rocks, if it could be broken by crack propagation mode or not, should be taken before drill bit selection. This can be checked even from the drill cuttings also in absence of its re-grinding. Further, in absence of detailed rock properties measurements, an earlier established model of similar rocks with log data may be helpful.

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Nomenclature

UCS = unconfined compressive strength, σ_c

σ_t = tensile strength

C_0 = shear strength at unconfined

K_{IC} = fracture toughness (crack opening)

K_{IIC} = fracture toughness (crack shearing)

WOB = weight on bit

TOB = torque on bit

$ISRM$ = international society of rock mechanics

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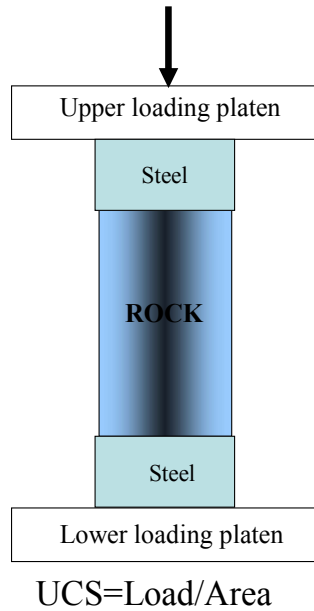


Figure 1a: Compressive Strength

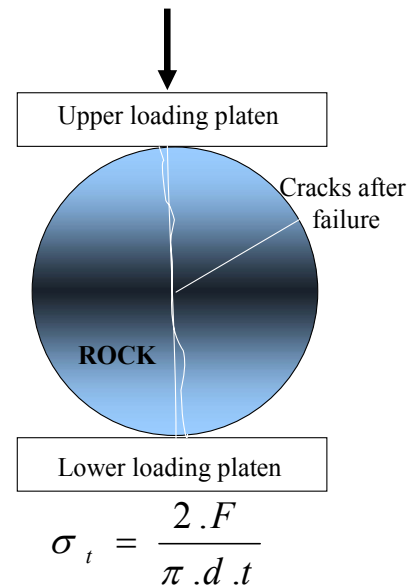


Figure 1b: Brazilian Tensile Strength

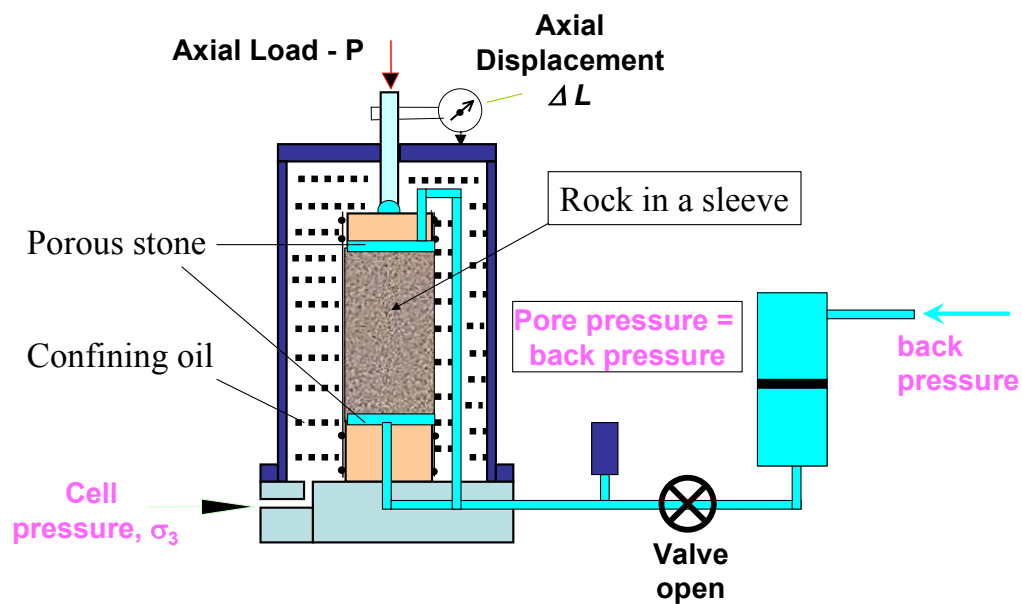


Figure 1c: Shear Strength by Tri-axial Set-up

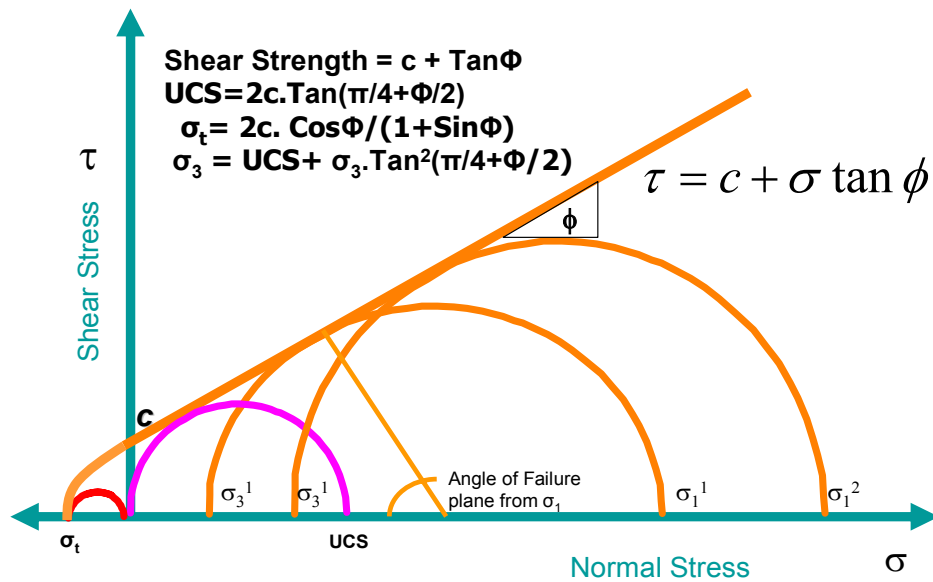


Figure 2: Mohr-Coulomb Failure Envelope

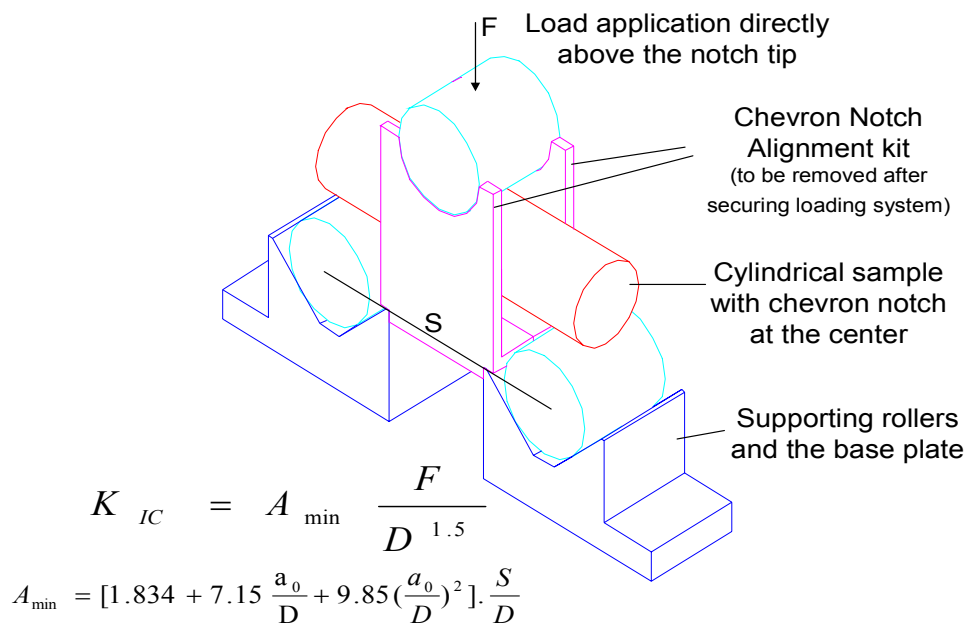


Figure 3: Fracture toughness by 3-point bending method

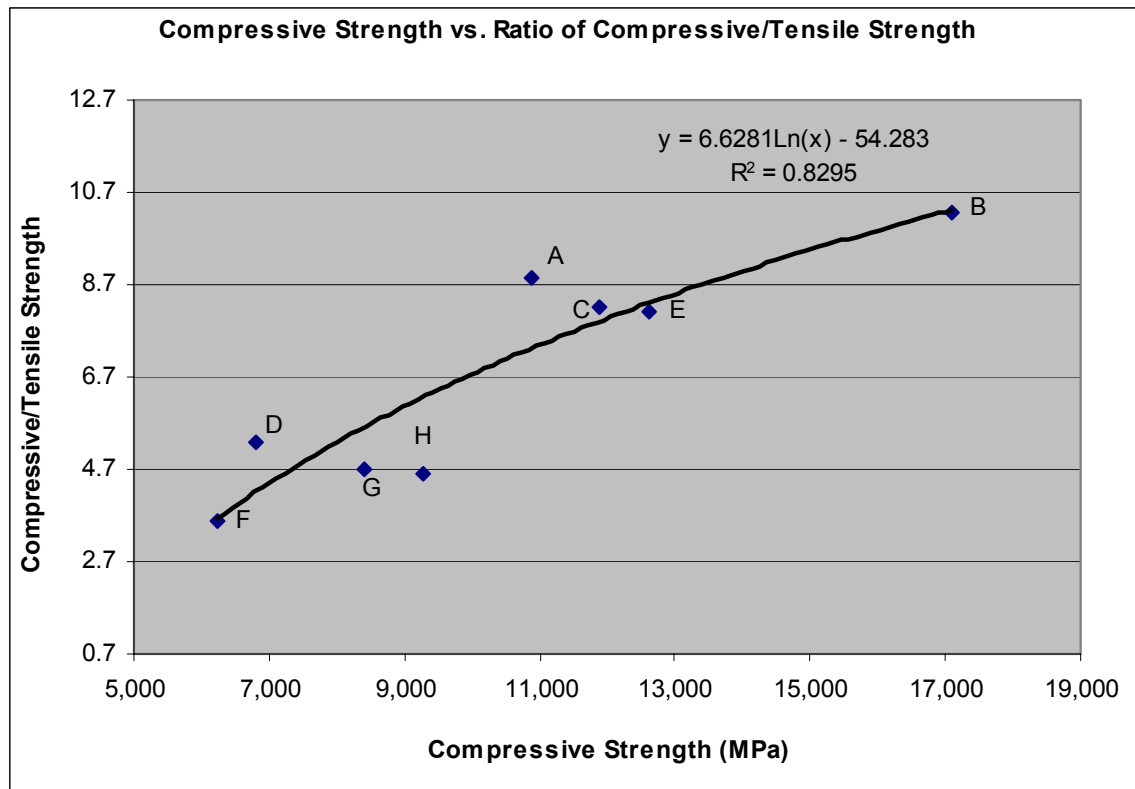


Figure 4: Ratio of Compressive to tensile strength vs. Unconfined Compressive Strength

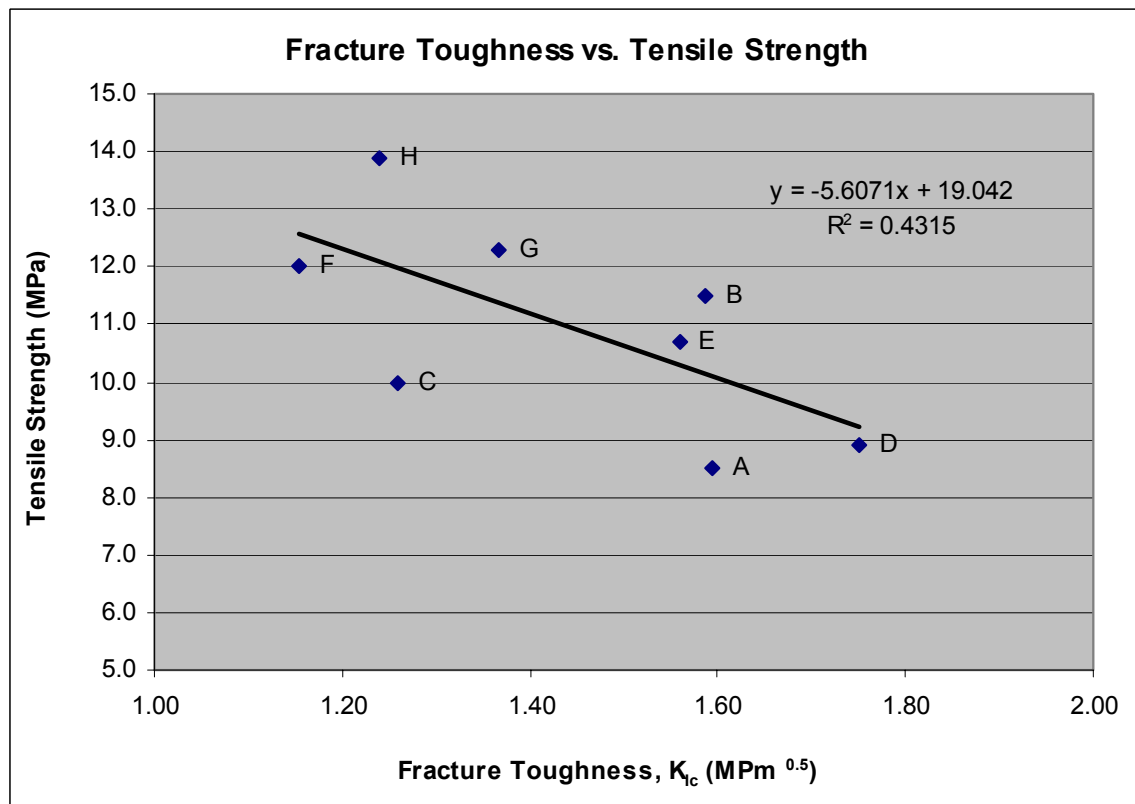


Figure 5: Fracture Toughness vs. Tensile Strength

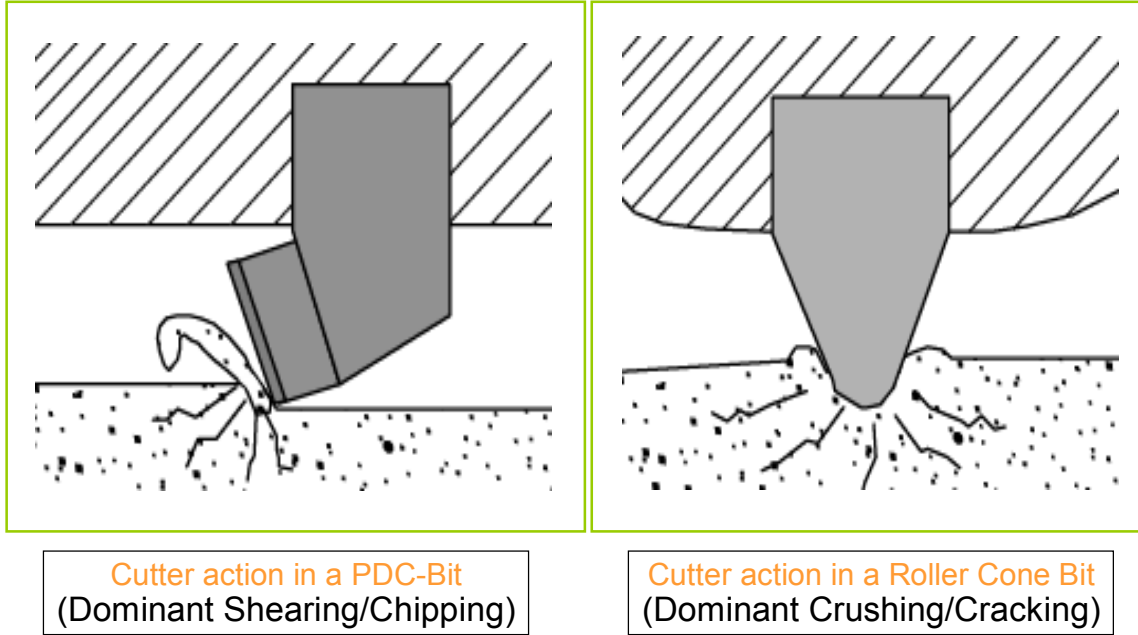


Figure 6: Schematic diagram showing cutter actions in PDC and Roller cone Bits