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CORRELATION DEVELOPMENT BETWEEN INDENTATION PARAMETERS AND UNAXIAL COMPRESSIVE STRENGTH FOR COLOMBIAN SANDSTONES

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A new way to characterize the perforated formation strength has been implemented using the Indentation test. This test can be performed on irregular cuttings mounted in acrylic resins forming a disc. The test consists of applying load on each sample by means of a flat end indenter. A graph of the load applied VS penetration of the indenter is developed, and the modules of the test, denominated Indentation Modulus *(IM)* and Critical Transition Force *(CTF)* are obtained (Ringstad *et al*., 1998). Based on the success of previous studies we developed correlations between indentation and mechanical properties for some Colombian sandstones. These correlations were obtained using a set of 248 indentation tests and separate compression tests on parallel sandstone samples from the same depth. This analysis includes Barco Formation, Mirador Formation, and Tambor Formation. For the correlations, IM-UCS and CTF-UCS, the correlation coefficient are 0,81 and 0,70 respectively. The use of the correlation and the Indentation test is helpful for in-situ calibration of the geomechanical models since the indentation test can be performed in real time thus reducing costs and time associated with delayed conventional characterization.

Keywords: *rock mechanics, perforation (well), sandstone, soil, characterization, electric log, Mirador formation, Barco formation, K1 Inferior formation, Tambor formation, Piedemonte Llanero, Colombia.*

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Una nueva manera de caracterizar la resistencia de las formaciones perforadas ha sido implementada por medio de una prueba denominada Indentación. Esta prueba es desarrollada sobre cortes irregulares de roca encapsulados en resina acrílica formando un disco. La prueba consiste en la aplicación de carga sobre cada partícula de roca por medio de un indentador de punta plana. En la prueba, una gráfica de la carga en función del desplazamiento del indentador en la muestra es registrada, en dicha gráfica se calculan los parámetros de indentación denominados Modulo de Indentación (IM) y Fuerza Crítica de Transición (CTF) (Ringstad *et al*., 1998). Con base en estudios previos se desarrollaron correlaciones propias entre los parámetros de Indentación y el UCS (Resistencia Compresiva Uniaxial) para algunas formaciones de areniscas Colombianas. Dichas correlaciones se obtuvieron llevando a cabo 248 pruebas de Indentación y paralelamente 21 pruebas de Compresión Uniaxial sobre muestras provenientes de cilindros de roca de geometría convencional. Este estudio incluyó muestras de las formaciones: Mirador, Barco y Tambor. Para las correlaciones IM-UCS y CTF-UCS se determinaron coeficientes de correlación de 0,81 y 0,70 respectivamente. El uso de las correlaciones y las pruebas de Indentación es muy útil para la calibración de modelos geomecánicos en tiempo real ya que las pruebas pueden hacerse directamente en campo, reduciendo los costos y tiempo asociados con la caracterización convencional.

Palabras clave: *macánica de rocas, perforacoón (pozos), areniscas, suelos, caracterización, registros eléctricos, Formación Mirador, Formación Barco, Formación K1 Inferior, Formación Tambor, Piedemonte Llanero, Colombia.*

INTRODUCTION

The strength of rocks is a crucial property in studies on mechanical stability of wells. The analysis of the drilling parameters on the Colombian Foothills area showed that rock strength commonly known as UCS (Uniaxial Compressive Strength) predicts the behavior of wellbore stability. While outlining a Statistical Geo-mechanical Study for stability During the Drilling Process in Recetor Field, it was found that UCS of formations is the highest influence variable above factors such as azimuth, slope, exposure time and even the mud weight (Jaramillo, 2004).

Traditionally speaking, the strength characterization of subsurface is made from electric logs taken after the drilling or based upon mechanical tests made in core samples. It is not always possible to characterize all the formation by applying the conventional characterization techniques (electric logs and laboratory test). Logs are commonly affected by uncontrollable factors such as the condition of the borehole. Electric logs not always can be run completely in the programmed interval because of operational problems besides the fact that many times there are long intervals in the well where electric logs are not programmed to be taken. Additionally logs are not always continuous along the well. On the other hand, the coring interval which are used to do conventional technique test are obtained in very short intervals. Besides, laboratory tests are run with very low frequency, as the cores withdrawal results in a huge impact of technical and operative types in the drilling process and generally this sample taking is done only on the area of interest of the well. In both cases the indentation test can help to characterize such zones.

When profiles of subsurface mechanical properties are built from electric logs, it is necessary to make a further calibration, often based on laboratory data. In general an appropriate correlation between the physical behavior and formation strength should be developed from laboratory tests made on rock cores (Chandon Chang, 2004). Since in most cases the recovery of cores is limited to the area of interest, there is a lack of information about real values over most of the borehole. This lack of information has encouraged the industry to develop non conventional techniques and methodologies such as the Indentation test to estimate rock strength. Previous studies have confirmed that indentation tests made on small samples can be used to obtain mechanical rock parameters (Ringstad *et al*., 1998). In 1996, AGIP (trademark of the Italian group ENI) presented a program capable of assessing formations, based on measurements on drilling cuttings. This work lead to the conclusion that contrary to what we think, drill cuttings are sufficiently representative of the formation and are a reliable source of information about their mechanical behavior (Santarelli *et al*., 1996). Important applications of indentation measurements are reported in recent publications by Zausa *et al*., (1997) where the indentation test together with other tests also made on drill cuttings provide information to support operational decisions regarding stability problems. The indentation test information has also been used as part of a methodology to optimize the screening system of the drilling bit (Uboldi *et al*., 1999). These works have implemented the test using correlations between the Indentation Modulus and the UCS developed on sandstones, limestones, and shales of different strengths and rigidities (Ringstad *et al*., 1998).

Since the mechanical response of rocks vary according to their type, this work has targeted a research seeking to establish specific correlations for the different lithologies such as sandstones. Shales and limestone studies will be published in the future. This work supports and extends previous efforts in determining UCS from the Indentation test when the UCS values range between 16-210 Mpa. The implementation of Indentation in field can help to decrease operational costs when dealing with problems related with wellbore stability, as such testing provides the companies with the opportunity of determining mechanical properties directly in field while drilling works are performed, at low cost and with very low impact in drilling (Ringstad *et al.,* 1998), aspect which improves with this work, deducing correlations by lithology.

Besides the decreasing operational costs, indentation tests offer the following advantages:

1. Testing procedures are relatively simple and the results are sufficiently reliable to properly determine the formation strength.

2. Portable equipment is readily available allowing the possibility of applying the methodology in real time.

3. Information can be gathered along the entire section of the well.

4. The test is inexpensive test (Uboldi *et al*., 1999)

METODOLOGY

The methodology used to develop the correlations consisted of running standard unconfined compression tests on rock cylinders and indentation tests on lab samples simulating drilling cuttings obtained from the UCS sample cylinder. The indentation test allows us to obtain two average parameters: IM and CTF while the unconfined compression test yields the UCS. Correlations are examined by constructing cross-plots of the UCS versus IM and UCS versus CTF.

This research work was focused on the development of correlations for sandstones with a strength range of 15-210 Mpa. The initial testing program included 30 cylindrical sandstone samples (diameter = 1" and length = 2"). However, only 21 samples were found acceptable for testing. A disk (approximately 5 mm thick) was cut from the ends of each of the samples used for the indentation tests (Figure 1). The disk was fragmented before indentation tests were run (Number of tests according to the experimental design in section Experimental Design). This is optimized sampling without altering the integrity of the test specimen. After tests were carried out, the average parameters of indentation were calculated and compared with the measured UCS.

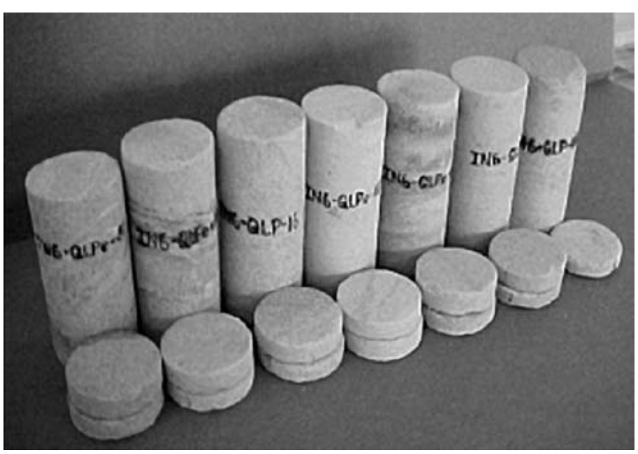

Figure 1. Unconfined compression test specimens (1"x2") and (~5mm thick) used in Indentation test

INDENTATION TEST

To run the Indentation tests, rock particles having a minimum diameter of 4 mm, further they were mounted on acrylic resin forming a disk of 1cm of thickness and 2,5 cm of diameter approximately. In total about 50 disks were manufactured. Disks were ground and then polished to expose the rock fragments. This procedure concurrently produces flat and parallel surfaces. Each of these disks was mounted in the materials testing equipment, MTS-810, of the Materials Strength Laboratory of the Instituto Colombiano del Petróleo (ICP). Load was applied by means of a flat end indenter achieving a penetration depth of 0,3 mm moving at a speed of ,01 mm/s. Displacement and load were recorded as the tip penetrated each rock fragment.

The Indentation Module and the Critical Transition Force of a sample rock represent the strength opposed by the sample rock to be penetrated. These modules feature an excellent correlation with the Uniaxial Compression Strength UCS of rocks (Ringstad *et al*., 1998). The most important application is the possibility to determine UCS indirectly by making measurements directly on drilling cuttings. The use of a correlation as well as the conventional tests of laboratory do not accurately reflect the large scale formations properties, since these properties are influenced by faults, heterogeneities, weakness planes; therefore the use of these values in engineering applications should be accompanied by the engineer's criterion.

Equipment

Figure 2 shows schematically the changes required to a standard testing machine to carry out indentation tests. The LVDT (Linear Variable Differential Transducer) that registers the penetration depth of indenter, while the load cell measures the force.

The loading device can operate in the load or displacement mode. The recommended displacement speed should be 0,01 mm/s. The equipment must be capable of controlling minimum penetrations on the order of 0,1 mm.

The load is transmitted from the load body to the rock by means of an indenter: The indenter is a metallic piece with a solid cylindrical tip having 0,5 mm height

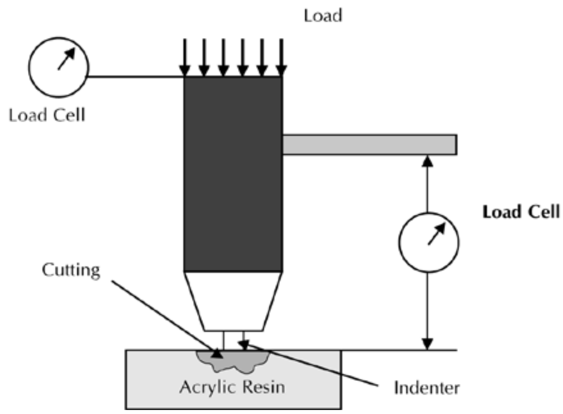

Figure 2. Indentation Equipment Layout

and 1 mm of diameter. The contacting surface should be flat. The indenter manufacturing material is selected to minimize the penetrator deformation at maximum load. The equipment used in this work was de Material Test System of the Materials Strength Laboratory (Ecopetrol S.A. - ICP, Figure 3).

For rocks having an estimated Uniaxial Compressive Strength (UCS) of less than 220 Mpa, the indenter can be manufactured from tool steel with a Rockwell hardness greater than or equal to 63.

Experimental design

The presentation of correlations requires the use of average parameters of indentation because they correspond to experimental measurements. The number of values required to make the mean representative is a function of the sample heterogeneity and size. For well consolidated sandstones, the standard deviation of Indentation modulus is about σ = 1,0 KN/mm. For sandstone of low consolidation σ = 1,2 KN/mm. These values together with expected errors ε = 1,25 KN/mm allow us to calculate the necessary tests to obtain average values of Indentation Modulus, IM, and Critical Transition Forces, CTF, using the following formula of statistical theory.

$$n = 4\left(\frac{z_{\alpha/2} * \sigma}{\varepsilon}\right)^2 \quad (1)$$

Where n = number of tests, $Z_{\alpha/2}$ = area under the normal distribution curve, σ = standard deviation and ε = Expected error in the confidence interval.

Calculations indicate that for high consolidation rocks, at least 10 indentation tests are required while 15 tests are needed for low consolidation sandstones.

Samples preparation

The Indentation tests are used to derive information about the mechanical behavior of rocks from measurements on drill cuttings. The irregular size and shape of drill cuttings need to be addressed so that it does not influence the outcome of the test. In this case, the indentation requires a flat and perpendicular surface to the indenter, additionally certain irregular shapes like drill cutting require preparation to make them stable under loading conditions. To solve this problem, rock fragments were encapsulated within an acrylic resin, which becomes a rigid disk containing such fragments after the curing process. The indenter geometry (diameter = 1 mm) allows to apply a high stress to the rock particle, then the load applied is supported by the sample which in terms

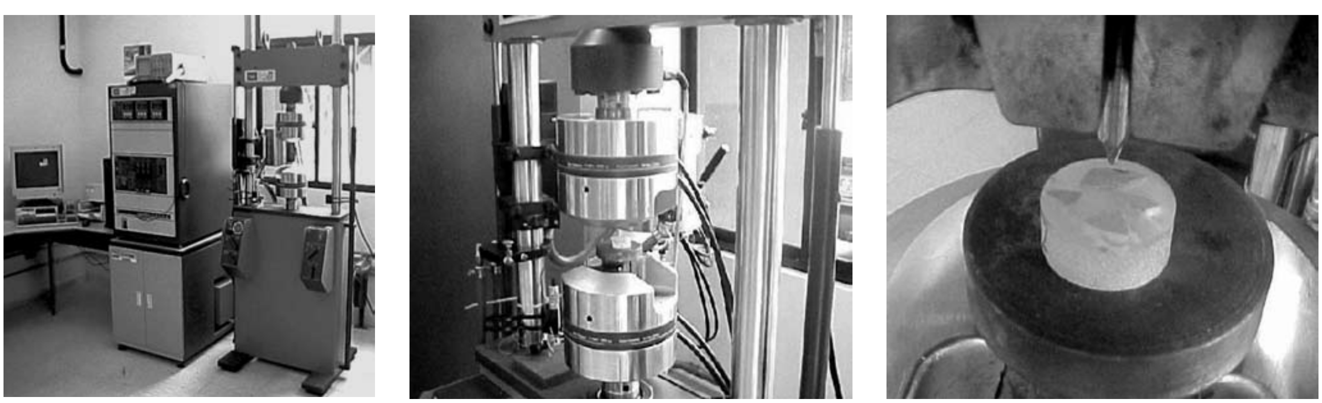

Figure 3. Materials Testing Equipment

of stress in not representative compared whit the stress applied to the rock particle. It was found that, in terms of strain, the test is not affected due to the high stiffness of the acrylic resin.

The study did not use cuttings obtained from drilling; instead rock particles from a cylinder were used to simulate drill cuttings. The manufacturing of the test specimens required for cylindrical casts is made by placing the rock fragments in a mould and covering the fragments with a resin. After curing, the specimen is removed from the mould and ground and polished until the maximum surface area of the fragments is exposed. This process can be carried out using emery and a grinding machine. This process is manually intensive; however it leads to the best test specimens.

Indentation curve

The indentation test results in a load (KN) versus penetration (mm) graph where it is possible to differentiate three areas. The proportionality zone, the transition zone and fracturing (Figure 4).

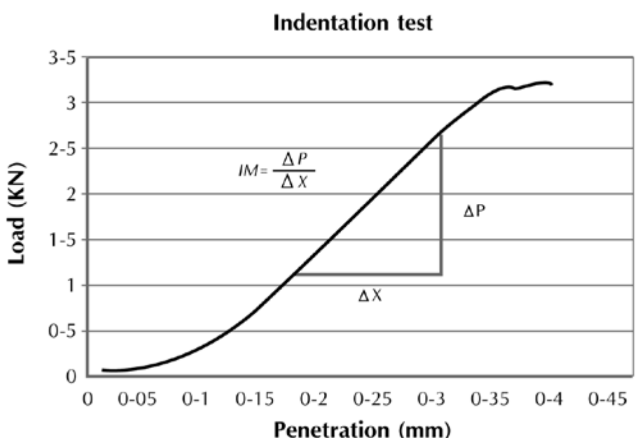

Figure 4. Indentation Modulus, *IM*, calculation is performed in the linear proportionality range

IM Calculation

The Indentation modulus is obtained directly from the load versus penetration curve. The Indentation modulus is calculated as the slope of load versus penetration curve in the proportionality zone (Figure 4). The Indentation Modulus units are Newtons per millimeters (N/mm). This calculation, is made load penetration curves for each exposed fragment. The average or mean value is then calculated over all measured fragment from that rock.

$$IM = \frac{\Delta P(KN)}{\Delta X(mm)} \tag{2}$$

where IM = Indentation module (Ringstad *et al.*, 1998), ΔP = change in load and

ΔX = change in penetration.

CTF Calculation

The Critical Transition Force is obtained directly from the load versus penetration curve of the indentation test. The Critical Transition Force is calculated as the load level wherein the rock loses its linear behavior. This parameter has load units (KN). This load is calculated on the corresponding curve of each tested rock fragments. The average CTF value is calculated from an analysis of all fragments tested.

In a previous stage of the study, a set of 100 tests was done over rock fragments originated from the same sample in order to observe Indentation Module (IM) and Critical Transition Force (CTF) statistical data distribution. From these tests, a normal distribution behavior based on the belt-shaped density curve, with low spreading (Figure 5), was observed for the IM.

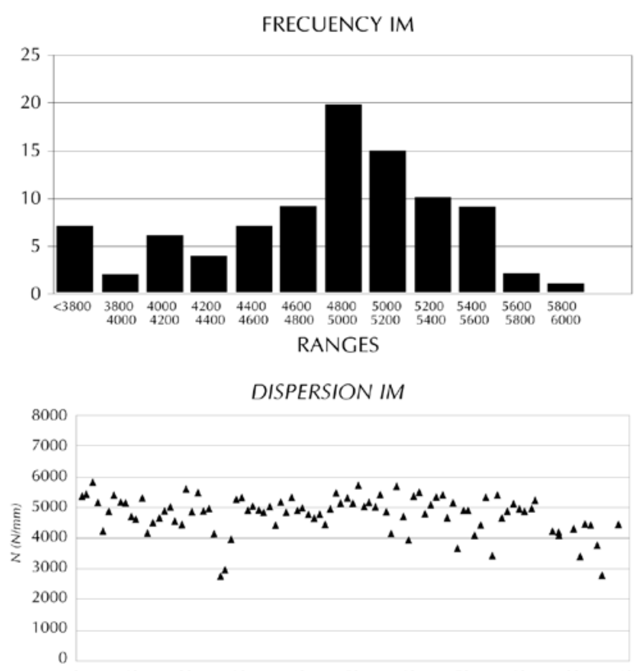

Figure 5. Frequency histogram and spreading diagram IM

The CTF also shows this kind of distribution but it has a higher scattering (Figure 6). Frequency histograms and scattering plots show that there is a well defined average tendency.

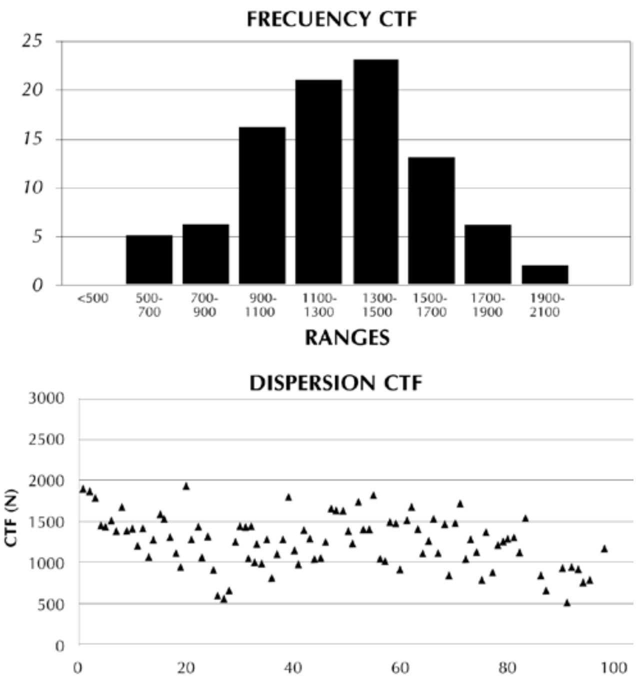

Figure 6. Frequency histogram and spreading diagram CTF

RESULTS

Figure 7 shows a load-penetration curve obtained for the Mirador Formation sample QLP-23, where the curve is the result of a test run on a rock fragment. For each specified sample (cylinder) as seen in Table 1,

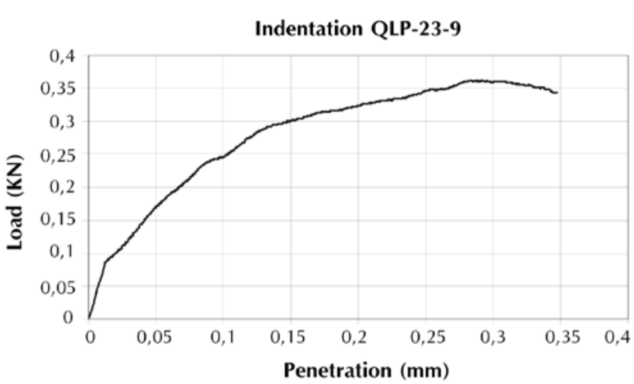

Figure 7. Indentation test for sample QLP-23-9 from the Mirador formation

there exists a family of curves similar to those in Figure 8, which implies that 21 curves families for a total of 250 indentation curves was made.

As described above the indentation test results in a load (KN) VS Penetration (mm) graph. Here, one can see three different zones. The first area or proportionality area, wherein the load applied to the rock is directly proportional to the indenter penetration into the rock, which is the zone where IM is estimated. Out of test QLP- 23-9 (Figure 7) an IM=2,0102 KN/mm is procured. There is a second area known as the transition area, in which the CTF is determined. This zone is characterized for the fact that the curve changes its linear behavior into a behavior that is more constant in terms of load, which at times is unpredictable. Taking into account that in such zone of the graphic the sample fracture takes place and that shear failures in this case are violent the response of the graphic in this area is unpredictable. Due to the fact that that the modules have been calculated in the preceding zones the test is not affected. In this area, the interest lies in the inflection point, which determines the change herein described which is called Critical Transition Force. Out of the test QLP-23-9 (Figure 7) it is possible to detect a CTF = 0,22 KN. The third area is characterized for showing large displacements without a noticeable increment of load. In this zone of chaotic behavior in comparison with the preceding areas, the reason is that after CTF the sample fractures, and for the case of sandstones formations which in general terms fail violently due to their brittle conditions, in this area the behavior is irregular as the rock has lost its monolithic character.

However, for a certain sample it is possible to trace not only one curve but also a set of curves, for finally obtaining the average parameters. Figure 8 shows ten (10) graphs corresponding to the series of curves obtained for fragments from sample QLP-23. The average measured value of IM is 2,29 ± 0,752 KN/mm and the average value of CTF is 0,241 ± 0,0495 KN. The standard deviations are useful in assessing the repeatability of the tests. Frequency histograms of IM and CTF are shown in Figures 9 and 10; note that most data are located around the mean value.

In total about 250 indentation tests were carried out on rock fragments corresponding to 21 sandstones samples having different strengths and rigidities (strength range is 16 - 210 Mpa). The results are shown in Table 1.

Table 1. Resuls of Indentation Test

Sample	IM			CTF			UCS (Psi)	UCS (Mpa)
	IM (KN/mm)	Standard Deviation	CV (%)	CTF (KN)	Standard Deviation	CV (%)		
tambor 17	4,29	1,08	25,13	1,63	0,41	25,41	12979,17	89,49
tambor 22	4,76	0,43	9,12	1,13	0,10	8,96	14003,31	96,55
tambor 23	3,47	0,51	14,72	0,79	0,18	22,25	10475,61	72,23
tambor 26	4,32	0,72	16,78	1,78	0,41	23,27	12022,80	82,89
tambor 28	4,71	1,03	21,78	0,85	0,17	20,06	14316,14	98,70
tambor 30	4,35	0,96	22,07	0,75	0,15	20,35	12793,31	88,21
Tambor 16	4,99	0,43	8,63	0,76	0,09	12,26	15786,45	108,84
T3-1	7,31	1,07	14,59	0,98	0,23	23,13	13050,67	89,98
Cup A1-1	10,72	1,02	9,51	2,16	0,31	14,38	30321,12	209,05
Cup A1-2	10,17	1,34	13,17	1,72	0,25	14,44	28644,11	197,49
QLPE-80	3,36	1,08	32,24	0,35	0,08	23,09	2267,00	15,63
QLP-102	4,56	1,17	25,68	0,51	0,05	9,75	7159,41	49,36
QLP-106-2	4,17	1,52	36,48	0,44	0,10	22,22	3843,90	26,50
QLP-23	2,29	0,75	32,91	0,24	0,05	20,59	5786,88	39,90
QLP 106-1	3,14	1,32	42,13	0,29	0,04	15,38	3928,89	27,09
QLP 16	2,59	1,25	48,40	0,24	0,04	16,87	2982,00	20,56
APIAY 11 10482	7,54	0,51	6,75	1,14	0,24	20,69	17939,82	123,69
T1	6,11	0,83	13,60	0,96	0,17	17,56	16445,15	113,38
T2	5,80	0,52	8,99	0,86	0,11	12,92	11577,50	79,82
T3	5,36	1,14	21,25	0,98	0,22	22,37	16860,34	116,25
T4	7,25	1,22	16,77	0,99	0,30	30,39	18258,45	125,89

90,5% of the testing groups have a CV between 6% and 36% for their measured values of IM. Samples QLP-106-1 and QLP-16 feature a CV of 42% and 48% respectively, which can be related to their low resistance. The IM of QLP 23 also shows a CV of 32%. For CTF the value of CV is between 8% and 31%. A very important observation is that in the samples of less resistant rock possess the highest values of standard deviation, which suggests to reduce uncertainty, it is advisable to increase the number of fragment tests.

The set of values used of IM and CTF to specify the correlations with the Uniaxial Compressive Strength (UCS) include a confidence interval, which is represented by an average value with a range of values delimited by the mean value more or less the standard deviation (Table 1).

IM data were correlated with their respective UCS data. In this data set a linear regression type was made as seen herein below: Linear regression between UCS and IM yields:

$$UCS = 17,38*IM \qquad R^2 = 0,81 \tag{3}$$

The positive slope (Figure 11) implies a positive correlation between UCS and IM.

CTF values were correlated with their corresponding UCS measurements The linear regression result is:

$$UCS = 91,97*CTF \qquad R^2=0,70 \tag{4}$$

This function is plotted in Figure 12.

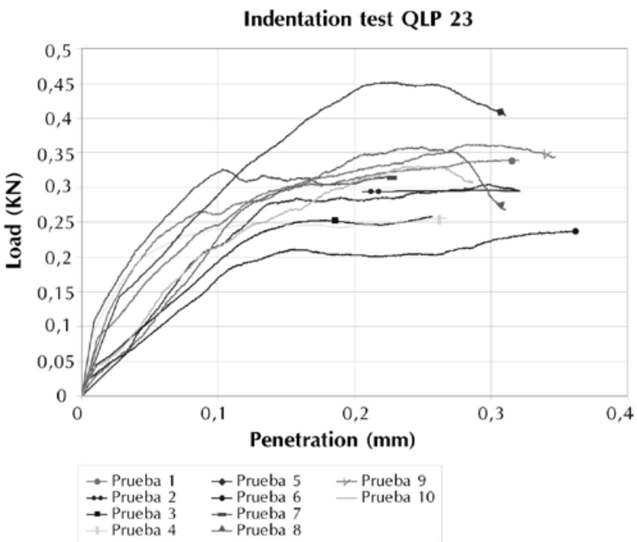

Figure 8. Family of curves, showing the Indentation test in Mirador formation outcrop. QLP-23

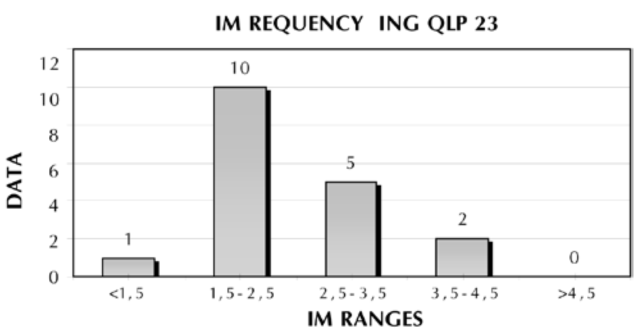

Figure 9. Frecuency Histogram: IM Mirador, QLP-23

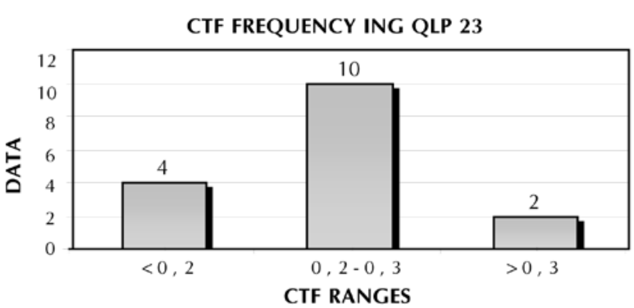

Figure 10. Frecuency Histogam: CTF Mirador, QLP-23

DISCUSSION OF RESULTS

The observation of curves in Figures 11 and 12 indicate that the indentation test reflects the rock strength;

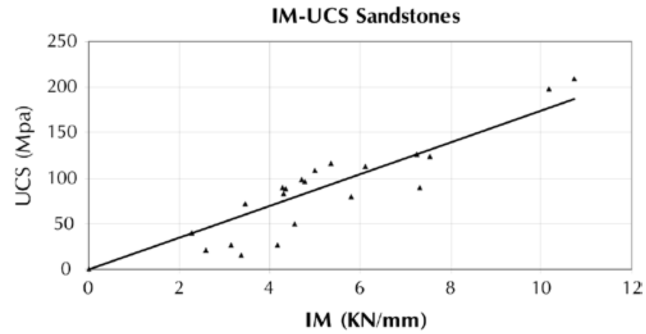

Figure 11. Graph of correlation UCS-IM (Sandstones)

the largest values of IM and CTF are correlated with the greatest strengths. The magnitudes of the Indentation Modulus and corresponding values of UCS show that the indentation parameters can be taken as a rock mechanical characteristic.

In the plot of CTF versus UCS (Figure 12) three sets of values are seen, firstly the points corresponding to the outcrop of Mirador formation; secondly, the Tambor formation points appear and third we find the points corresponding to fresh samples from Mirador formation. It is obvious that UCS values also occur in the same sequence, which allows us to conclude that the CTF modulus can be used as a characteristic of the rock. The same order is seen with the cloud of points in Figure 11 for IM versus UCS.

Figures 11 and 12 feature a clear tendency of correlation among each of the indentation parameters with UCS where it is shown that the tendency is adequately captured in linear relationship with positive slopes. Similar results were reported by Rinstad *et al*., (1998). Results presented by Zausa (1997) and Santarelli (1996)

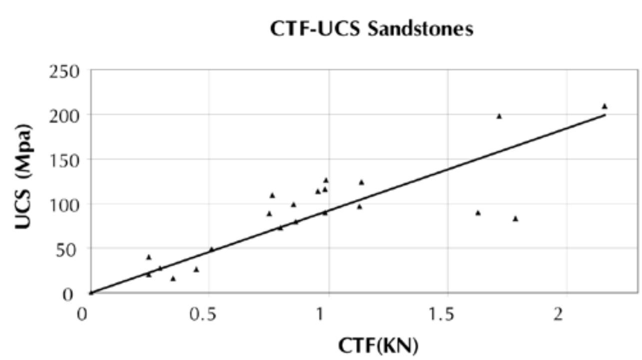

Figure 12. Graph of correlation CTF-UCS (Sandstones)

are better fit to an exponential function. The functional forms reported in previous work as well as this work are shown in Figure 13.

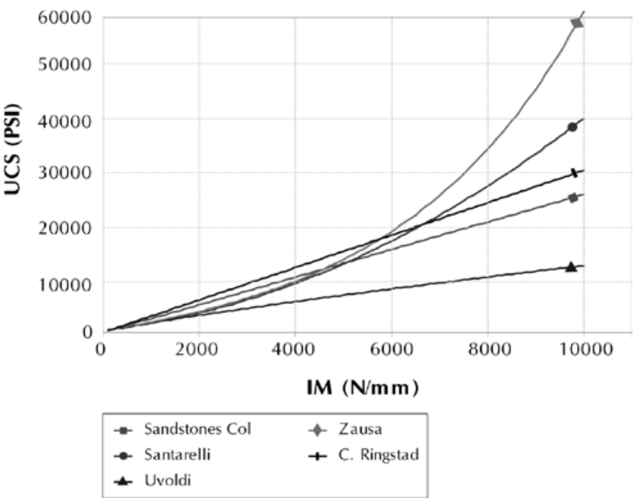

Figure 13. Comparison between published correlation and correlation developed for Sandstones

In this work the correlation obtained for sandstone over a range of 0 and 5500 N/mm coincides with the correlations of Santarelli *et al*., (1996) and Zausa *et al*., (1997) but after this interval, correlations are divergent. If correlation for sandstone is compared to the correlation presented by Ringstad *et al*., (1998) and Uboldi *et al*., 1999, it is evident that these correlations are similar (linear) but they differ slightly slopes.

Standard deviations σ and variation coefficients CV, of indentation parameters show once again that rocks are heterogeneous, both at the micro and macro-structural levels. The families of curves were obtained from the same sample (as explained in the methodology section), nevertheless the variation coefficient CV of IM shows that values corresponding to 23% of these values are above 30% of CV. The CTF modulus shows a better convergence with one value above 30% of variation coefficient CV, corresponding to 4,76%, as seen in the histogram of frequencies (Figure 14).

The CV previously defined allows eliminates the dimensionality of variables and preserves the proportion between the mean value and the standard deviation of a data set. Using this statistical approach, it is possible to compare the scatter among data groups.

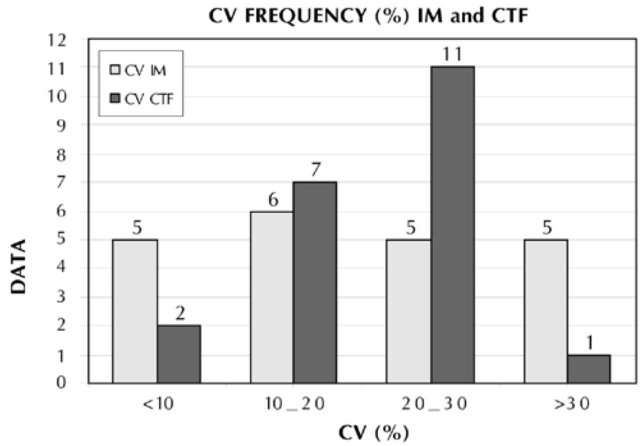

Figure 14. CV Frecuency IM and CTF data set

Figure 14 shows the CV frequency corresponding to IM (rectangles) where it is observed that 77% of such coefficients are below 30%. In other words, 23% of 21 groups of data have a scattering of over 30%. Scattering taken as the measure of accuracy is measured using CV. The calculated UCS values using the equations developed have some margin of error.

When comparing the correlation coefficients obtained from least square method and calculated for the sets of Indentation Modulus and Transition Critical Force, it is possible to see a better correlation between IM and UCS. An explanation of the above case, can be the similarity of the physical meaning of the two tests, that is, the indentation test has a greater physical resemblance to the Unconfined Compression Test, since load is applicable to both tests until the specimen is taken to its maximum strength point. This means that the modulus known as Indetation Modulus could be physically compared to the strength of the rock, known as UCS or Uniaxial Compressive Strength.

Rocks of smaller strength feature more scattered Indentation Modulus (IM) (Figure 15). This is a conclusion drawn from results corresponding to tests run on outcrop samples of Mirador formation, which fact is reflected in that repeatability of the parameters of the test depends on the consolidation of tested samples and therefore its strength. This mean that, for low resistance rocks it's necessary doing more tests than for high strength rocks, to obtain a representative average of IM.

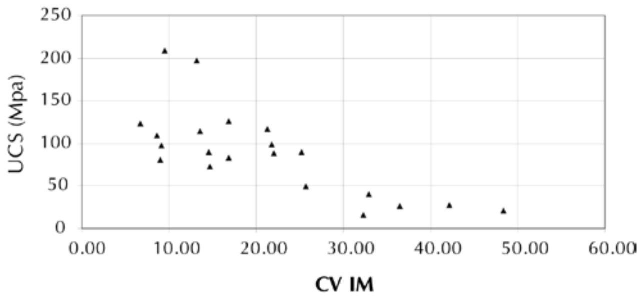

Figure 15. CV Frequency IM and corresponding UCS

Correlations obtained clearly show correspondence between the indentation test and the UCS for the samples tested; nevertheless, the fact that the samples tested are not a drill cuttings creates some uncertainty in the direct application in the field and for doing direct metering on drill cuttings at a wellsite.

CONCLUSIONS

- Based upon the correlation coefficient results obtained for the sets of IM versus UCS and CTF versus UCS data, we can conclude that there exists a very strong correlation between the parameters of the Indentation test with the strength values. The correlation coefficients for the linear fits are 0,81 and 0,70, respectively. The two statistical models show the good correlation between the two tests and the viability of their use to characterize the strength of real-time drilled formations. This implies that indentation parameters can be taken as a mechanical characteristic of rocks.

- It was found that Indentation modulus values obtained for low consolidation sandstone samples feature greater scatter than the Indentation modulus of highly consolidated sands. This is concluded upon observing the CVs calculated for samples QLP-80, QLP-102, QLP-102-6, QLP-23, QLP-106-1 which coincide with the lower mechanical strength values.

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