Iraqi Geological Journal

Journal homepage: <https://www.igj-iraq.org>

Mechanical Rock Properties Estimation for Carbonate Reservoir Using Laboratory Measurement: A Case Study from Jeribe, Khasib and Mishrif Formations in Fauqi Oil Field

Qahtan A. Abdul Aziz^{1,*} and Hassan A. Abdul Hussein¹

¹ Petroleum Engineering Department, College of Engineering, University of Baghdad

* Correspondence: Kahtanadnan72@yahoo.com

Received: 17 January 2021; Accepted: 6 April 2021; Published: 31 May 2021

Abstract

Estimation of mechanical and physical rock properties is an essential issue in applications related to reservoir geomechanics. Carbonate rocks have complex depositional environments and diagenetic processes which alter the rock mechanical properties to varying degrees even at a small distance. This study has been conducted on seventeen core plug samples that have been taken from different formations of carbonate reservoirs in the Fauqi oil field (Jeribe, Khasib, and Mishrif formations). While the rock mechanical and petrophysical properties have been measured in the laboratory including the unconfined compressive strength, Young's modulus, bulk density, porosity, compressional and shear -waves, well logs have been used to do a comparison between the lab results and well logs measurements. The results of this study revealed that petrophysical properties are consistent indexes to determine the rock mechanical properties with high performance capacity. Different empirical correlations have been developed in this study to determine the rock mechanical properties using the multiple regression analysis. These correlations are UCS-porosity, UCS-bulk density, UCS-Vs, UCS-Vp, Es-Vs, Es-Vp, and Vs-Vp. (*). For example, the UCS-Vs correlation gives a good determination coefficient ($R^2=0.77$) for limestone and ($R^2=0.94$) for dolomite. A comparison of the developed correlations with literature was also checked. This study presents a set of empirical correlations that can be used to determine and calibrate the rock mechanical properties when core samples are missing or incomplete.

Keywords: Petrophysical rock properties; Unconfined compressive strength, Shear P-wave velocity

1. Introduction

Rock mechanical properties are significant in establishing the plans associated with drilling, completion, stimulation, production, and reservoir monitoring processes (Meehan, 1994; Bjorlykke and Hoeg, 1997). When a piece of rock is subjected to sufficiently large stresses, some kinds of failures will occur. This implies that the rock shape will permanently change, and possibly fall apart. This condition is accompanied by reducing the ability to carry loads. Carbonate rocks are complex and thus rock mechanical properties are heterogenous (Tawfeeq and Al-Sudani, 2020). While rock mechanical laboratory testing is the most accurate method for calculating the rock strength (Rabbani et al., 2012). Core testing, unfortunately, can never lead to a continuous profile of rock strength along the wellbore.

DOI: [10.46717/igj.54.1E.8Ms-2021-05-29](https://doi.org/10.46717/igj.54.1E.8Ms-2021-05-29)

The coring is very expensive, and it is very sensitive to stress unloading. The number of core samples is also restricted due to time limitations as well as the availability of good quality core. Besides that, the lab results may not be fully representative of the entire reservoir section due to complex variations in rock composition (Rabbani et al. 2012). Rock failure is also an important phenomenon for petroleum related rock mechanics, as it is the origin of severe problems such as borehole instability and solids production. It is therefore useful to be able to predict under which conditions a rock is likely to fail (Raean, et al. 1996; Rabbani et al. 2012). The unconfined compressive strength (UCS) is the essential parameter for planning the mud weight window, bit selection and wellbore stability analysis. Besides, it is very important for reservoir subsidence and reservoir acidizing studies. When using this parameter, it is important to choose the proper weight on bit, evaluate drilling operation efficiency, bit wear and efficient bit lifetime in use (Nabaei et al. 2010, Rabbani et al. 2012). Several authors have been established many empirical correlations to estimate the mechanical properties (Militzer and Stoll, 1973; Sharma and Singh, 2010; Karamia et al. 2012; Castagna et al. 1993; Ameen et al. 2009; Change, 2004; Smorodinovet, et al. 1970; Khandelwal and Singh, 2009; and Karamia et al. 2012. Hadi and Nyaagred, 2018; Abdulmajeed and Alhaleem, 2020). Table 1 lists these studies along with the equations of the rock mechanical and petrophysical properties. The prediction of mechanical properties using petrophysical properties is more reliable, especially in carbonates rocks.

Table 1: Empirical correlations to predict the mechanical rock properties from petrophysical properties in carbonate

Model	Empirical Correlation
Militzer and stoll (1973)	$UCS=2.45VP^{1.92}$
Sharma and Singh (carbonate) (2010)	$UCS=36V_p-45.37$
Karamia et al. (2012)	$UCS=35.35V_s-7.588$
Castagna (limestone) (1993)	$V_s=0.4403V_p+0.576$
Castagna (dolomite) (1993)	$V_s=0.467V_p+0.5895$
Ameen et al. (carbonate rock) (2009)	$V_s=0.52V_p+0.25251$
Al-kattan (carbonate)(2015)	$V_p=0.699V_p^{0.969}$
Hadi and Nyaagred (carbonate rock) (2018)	$V_s=0.1206+0.44104V_p+0.1215p_{bulk}$
Abdul Majee and Alhaleem (carbonate) (2020)	$V_s=0.52V_p + 0.0562$
Change (for carbonate rock) (2004)	$UCS=143.8e^{-6.95\phi}$
Smorodinovet et al. (for carbonate rocks) (1970)	$UCS=0.88e^{2.85p}$
Khandelwal and Singh (limestone) (2009)	$E_s=4.9718V_p-7.151$
Karamia et al(limestone)(2012)	$E_s=8.804V_s+6.238$

Most of these models are empirical correlations established based on geophysical well logs, such as acoustic porosities or velocities porosities, to determine laboratory-derived mechanical rock properties (Yagiz, 2011). These correlations are based on the fact that several same factors that affect mechanical rock properties also affect physical properties, such as porosity, velocity, and elastic moduli (Chang et al. 2006). Generally, the relationships of mechanical rock properties and physical rock properties established for specific formation depending on the calibration of laboratory tests on rock samples from a specified field. The aim of this study is to correlate the rock mechanical properties with petrophysical properties using experimental work of many core samples that have been taken from three formations which are Jeribe, Khasib and Mishrif formations. This study has been conducted in the production section of the Fauqi oil field (South East Iraq). A major issue of this field is that no local empirical correlations can be used to determine the rock mechanical properties in terms of petrophysical for many applications related to geomechanics.

2. Geological Setting of the Study Area

Missan Oilfield is located in southeastern Iraq and close to the Iraq-Iran border. The field consists of three producing oilfields, namely Abu Ghirab, Buzurgan and Fauqi oilfields. Stru Fauqi oilfield has two sets of reservoirs, Tertiary Asmari and Cretaceous Mishrif. Three pay zones are divided in the Asmari reservoir which is A, B and C. The pay zone A of Asmari consists of mainly dolomite. The pay zone B is dolomite intercalated with sandstone, limestone and thin shale. The pay zone C is mainly the sandstone, intercalated with a few dolomite, mudstone and limestone. The main reservoir in the Fauqi oilfield is cretaceous Mishrif. Seven pay zones are divided in the Mishrif reservoir, which are MA, MB11, MB12, MB21, MB22, MC1 and MC2. More details about the studied formations are listed in Table.

Table 2. The geological description of the studied formations

Formation Name	Thickness (m)	Lithology	No. of Core Samples
Jeribe-Euphrates	2997.5-3046.07	dolomite intercalated with argillaceous dolomite, and conglomerate and locally anhydrite argillaceous	4
Khasib	3824.0-3886.0	limestone, with calcareous claystone on bottom.	4
Mishrif	3886.0-3939	Limestone interbed with thin argillaceous limestone	9

3. Materials and Methods

In this study, mechanical rock properties were determined using core samples collected from different reservoir intervals from different wells. Seventeen core samples of limestone and dolomite were obtained from Jeribe, Khasib and Mishrif formations in the FAUQI oil field. The length of studied cores is ranged from 2.3 cm to 4.43 cm, while the width is ranged from 2.34cm to 2.5 cm.

3.1. Uniaxial Compressive Strength (UCS) Test

The uniaxial compressive strength, or UCS, test is a destructive technique for determining the uniaxial compressive strength of intact rock core specimens. In rock mechanics and engineering geology, the UCS test considered to be the most widely used methods to obtain rock strength properties. Uniaxial compressive strength values (σ_f) were calculated using the following simple formula:

$$\sigma_f = \frac{F_f}{A} \quad (1)$$

where F_f is the force applied by the hydraulic cylinder to the sample at the time of catastrophic failure, A is the area of the ends of the sample, and is uniaxial compressive stress at failure that is equal to the UCS. Under the assumption that the material is isotropic one can also determine the Young's modulus E .

$$E = \frac{\sigma}{\varepsilon_{axial}} \quad (2)$$

and Poisson's ratio ν

$$\nu = \frac{\varepsilon_{radial}}{\varepsilon_{axial}} \quad (3)$$

where ε_{axial} and ε_{radial} are provided by the strain gauges mounted parallel and perpendicular to the cylindrical sample's axis, respectively. The lab apparatus used in this study for measuring the UCS, is shown in Fig.1. The experiment started with putting the core sample between two plates contacted

with the top platen. An axial load about 100 N is applied to core sample using the loading frame for fixing the core sample. The results are recorded with different axial forces until the core is crushed or fractured.

3.2. Ultrasonic Test

The velocity of propagation (V_p) and shear velocity (V_s) of core samples were measured with an ultrasonic device according to standard ASTM (1986) (Fig. 2). Measure the length or height of the specimen. Clean the upper and lower surfaces of the specimen and put little amount of any kind of grease on them to have complete adhesion between the specimen surfaces. put the specimen between the two transducers. Put the tester on to generate the pulse move the certain kind of P-waves and shear waves velocity could be obtained by using the two kinds of transducers each one specified fore wave shape on the oscilloscope to read out the arrival time of the wave the pointer must be the begin point of pulsation when recording the time. Measuring of primary waves velocity. The velocities of either P or S wave are calculated as follows:

$$V_p(\text{ or } V_s) = \frac{S}{t} \quad (4)$$

where VP is the P-wave velocity (km/s), VS is the S-wave velocity (km/s), S is the distance traveled by the wave (mm), and t is the travel time in this method, the wave frequency must be high, and the rock specimens must have infinite extent compared to the pulses' wavelength. This test is performed following the ISRM (2007). Fig. 3 shows several samples that were used before and after testing.

4. Results and Discussions

Table 3 represents experimental results of mechanical and physical rock properties for carbonate reservoir. Table 4 presents the JMP software's statistical output in terms of mean and standard deviation parameters for thirteen samples of limestones and four samples of dolomites for the involved properties.

Fig. 1. Apparatus of uniaxial compressive test for measuring of UCS and Es

Fig. 2. Apparatus of ultrasonic testing for measuring of P-wave and S-wave

Fig.3: core samples before and after uniaxial tests (A & B) for the Mishrif Formation, (C & D) for the Jeribe Formation (E & F) for the Khasib Formation

Table 3. Experimental results of mechanical and physical rock properties for carbonate reservoir

Depth	Lithology	Formation	UCS Mpa	Vp Km/Sec	Vs Km/Sec	Bulk density	Es	Porosity
3044	Dolomite	Jeribe	8.35	3.7	1.85	2.483	22.661	10.359
3022	Dolomite	Jeribe	5.095	2.25	1.285	2.305	9.571	12.863
3027	Dolomite	Jeribe	6.805	3.316	1.913	2.356	21.564	15.161
3945	Limestone	Mishrif	11.633	4.259	2.407	2.484	36.42	9.5
3814	Limestone	Khasib	12.12	3.916	2.232	2.433	30.529	11.019
3867	Limestone	Khasib	10.395	2.75	1.627	2.386	15.546	9
4035	Limestone	Mishrif	10.2	2.95	1.85	2.461	19.8	8.435
2988	Dolomite	Jeribe	12.427	4.387	2.835	2.75	50.458	3.47
4040	Limestone	Mishrif	4.2	2.85	1.61	2.206	14.47	15.02
3929	Limestone	Mishrif	14.1	5.25	3.04	2.65	61.12	6.2
4086	Limestone	Mishrif	10.04	3.52	2.2	2.38	27.17	9.8
3876	Limestone	Mishrif	16.12	4.85	3.47	2.7	63.43	5.7
3837	Limestone	Khasib	11.88	4.56	2.58	2.45	41.24	9.2
4102	Limestone	Mishrif	11.49	4.15	2.5	2.37	36	10.21
3835.5	Limestone	Khasib	12.8	5	2.77	2.66	52.19	9.8
4153	Limestone	Mishrif	15.21	5.76	3.27	2.78	64.24	4.3
4002	Limestone	Mishrif	11.99	4.61	2.6	2.53	43.33	10.32

Table 4. Summary of statistical data obtained from laboratory tests.

Parameter	Limestone (13 samples)		Dolomite (4 samples)	
	Mean	St. Dev	Mean	St. Dev
UCS (Mpa)	12.37	2.35	9.07	2.863
Vp (Km/s)	4.38	0.877	3.588	0.755
Vs (Km/s)	2.599	0.557	2.127	0.610
Bulk density	2.508	0.156	2.485	0.1
Es	46.14	15.685	34.6	15
Porosity	9.84	2.546	12	3.27

In the following sections, correlation between individual mechanical and physical properties will be presented separately as follows:

4.1 Correlation between Mechanical and Petrophysical Properties

4.1.1. Correlation between USC and S-wave Velocity

Fig. 4 shows the laboratory measured ultrasonic S-wave velocity (Vs) along with UCS results for limestone and dolomite samples. Two relationships between UCS and Vs have been presented where UCS in MPa and Vs in Km/sec. The results revealed that there is a scattering around the UCS–velocity curves. This can be attributed to the heterogeneity of carbonates formation which are mixed of dolomite intercalated with argillaceous dolomite in addition to conglomerate and locally anhydrite argillaceous (Jeribe Formation), and limestone interrelated with thin argillaceous limestone (Khasib and Mishrif

formations). In other words, this scattering is related to the complexity of pore rock system. Two correlations (Eqs. 5 and 6) have been constructed in this section, obtaining correlation coefficients (R^2) of 0.77 for limestone and (R^2) of 0.94 for dolomite, respectively. According to the results of Fig. 4, the results showed that UCS increases linearly with V_s (inversely with sonic travel times).

$$UCS = 4.409 \times V_s + 0.8045 \quad (5)$$

$$UCS = 4.732 \times V_s - 1.157 \quad (6)$$

4.1.2. Correlation between (UCS) and P-wave velocity (V_p)

Fig. 5 presents the relationships between UCS and compressional wave velocities for both limestone (13 samples) and dolomite (4 samples). The relationship between UCS and V_p is expressed in MPa and Km/sec, respectively. The results showed a clear scattering around each fit curve. This can be attributed to the different geological setting of limestone and the effect of the diagenetic processes on dolomite which altering the rock framework and pore structures to varying degrees. In addition, this scattering is related to the heterogeneity of formation because of the depositional environments and dolomitization processes.

Fig. 4. Relationship between uniaxial compressive strength and S-wave velocity

Two correlations (Eqs. 7 and 8) have been developed to correlate the rock strength with the compressional travel velocity for limestone and dolomite, respectively. Fig. 5 revealed that the rock strength increases with the compressional wave velocity. This supports the evidence that UCS decreases with increasing porosity (increasing sonic travel time or decreasing compressional wave velocity). A correlation coefficient (R^2) of 0.65 is for limestone while it is 0.89 for dolomite.

$$UCS = 2.28V_p + 1.939 \quad (7)$$

$$UCS = 3.304V_p - 3.1084 \quad (8)$$

Fig. 5. Relationship between uniaxial compressive strength and P-wave velocity

4.1.3. Correlation between uniaxial compressive strength and porosity

The relationship between porosity and UCS values is presented in Fig. 6. The porosity is a controlling factor of rock strength in the basalts that conducted in this study, most of the samples with relatively high porosities tend to be broken at very early stages in the load cycle which exhibit a very low UCS. On the other hand, most of the strong solid samples are associated with extremely low porosity. It also shows a strong correlation of $R^2=0.84$ between UCS and porosity for dolomite and $R^2=0.76$ for limestone according to the Equations 9 for limestone and 10 for dolomite.

$$UCS = 20.35 - 0.948\phi \quad (9)$$

$$UCS = 14.11 - 0.5679\phi \quad (10)$$

Fig. 6. Uniaxial compressive strength and porosity relationship

4.1.4. Correlation between uniaxial compressive strength and bulk density \

Fig. 7 shows the relationship between bulk density and UCS magnitudes for limestone and dolomite. A best-fit regression curve is obtained, showing a good correlation coefficient for limestone ($R^2=0.80$) and a best correlation coefficient for dolomite ($R^2=0.99$). In general, the rock matrix is mainly

composed of particles that have anisotropic arrangement, resulting a scattering between UCS and bulk density. The developed Equations are respectively 11 and 12 for limestone and dolomite, in which the rock strength (UCS) is linearly increased with the formation density, where UCS in Mpa and bulk density in gm/cc;

$$UCS = 16.34\rho - 29.13 \quad (11)$$

$$UCS = 15.64\rho - 30.52 \quad (12)$$

Fig.7. Relationship between UCS and bulk density

4.1.5. Correlation between compressional wave and shear wave velocity

The results of the laboratory ultrasonic measured velocities V_p and V_s for carbonate (limestone and dolomite) formations are presented in Fig. 8, where both V_s and V_p in Km/sec. Equations 13 and 14 outline the presented fit curve, obtaining equal R^2 of 0.88 for both limestone and dolomite, respectively. There is a scattering around each curve which can be attributed to the heterogeneity of carbonate samples in which the void proportions and pore size distributions within the rock fabric are complex.

$$V_s = 0.5704V_p + 0.08569 \quad (13)$$

$$V_s = 0.6729V_p - 0.326 \quad (14)$$

Fig. 8. Relationship between S-wave velocity and P-wave velocity

To validate our model, we compare the Equation from the core with the log data, as shown in Fig. 9 with $R^2=0.88$ for limestone and $R^2=0.91$ for dolomite.

Fig. 9. Plots of predicted Vs. using core data versus measured Vs. from log

4.1.6. Correlation between S-wave velocity and bulk density

Fig. 10 shows the relationship between S-wave velocity and bulk density of carbonate rocks. there are good relationships between S-wave velocity and bulk density with $R^2 = 0.76$ for limestone and $R^2=88$ for dolomite. The scatter in the data can be attributed to sample heterogeneities, matrix is mainly composed of particles. According to Equation 15 for limestone and Equation 16 for dolomite, S-wave velocity increases linearly with increasing bulk density. the equations of the relation are:

$$V_s = 3.175 \times P - 5.46 \quad (15)$$

$$V_s = 3.033 \times P - 5.532 \quad (16)$$

Fig. 10. Relationship between vs. and bulk density

4.1.7. Correlation between P-wave velocity and bulk density

Fig. 11 shows the relationship between P-wave velocity and bulk density of limestone and dolomite. The results support good relationships between P-wave velocity and bulk density with $R^2=0.73$ for limestone and $R^2=0.81$ for dolomite, Where V_p in km/sec and bulk density in gm/cc. The scatter of even the mean values around the regression lines is due to the complex depositional environments and diagenetic processes of carbonate rocks. According to Equation 17 for limestone and Equation 18 dolomite P-wave velocity increases linearly with increasing bulk density. the equations of the relation are:

$$V_p = 5.059 \times P - 8.547 \quad (17)$$

$$V_p = 4.073 \times P - 6.573 \quad (18)$$

Fig. 11. Relationship between P-velocity and bulk density

4.1.8. Correlation between young modulus and shear wave velocity

The regression curves between Young's modulus on S-wave velocity of carbonate rocks are shown in Fig. 12 and presented by Equation 19 for limestone and Equation 20 for dolomite. Determination coefficients (R^2) are 0.97 and 0.98 for limestone and dolomite, respectively. These direct correlations mean that increasing the rock Young's modulus causes an increasing in S-wave velocity.

$$E_s = 26.77V_s - 26.69 \quad (19)$$

$$E_s = 29.62V_s - 34.39 \quad (20)$$

Fig. 12. Relationship between young modulus and S-wave velocity

4.1.9. Correlation between young modulus and P-wave velocity

The regression lines of young modulus on the P-wave velocity of carbonate rock for the combined data are shown in Fig. 13 and presenting by equation 21 for limestone and Equation 22 for dolomite with determination coefficients of 0.93 and 0.84, respectively. The points are scattered uniformly about the diagonal line rock since the strength parameters are a function of physical, textural, and mineralogical properties of rock. Based on these correlations, an increasing in P-wave velocity (decreasing sonic travel time or porosity) increases the rock stiffness (increasing Young's modulus).

$$ES=17.67V_p-35.1 \quad (21)$$

$$ES=17.72V_p-34.41 \quad (22)$$

Fig. 13: Relationship between young modulus and P-wave velocity

4.2. Comparison between new correlations with the previous Empirical correlations

In this section, the developed correlations have been compared with some previous correlations in Table 1. The new correlation gives an excellent matching with Ameen (2009) and Castagna (1993) correlation but relatively less matching with Al-Kattan (2015) correlation for limestone formation.

Fig. 14. Comparison between Equation 13 and other empirical relation to predict Vs. for limestone rock formation from core data

the new correlation is compared with the other correlations for dolomite formation. The results show an excellent matching between the developed correlation, Ameen (2009) and Castagna (1993) correlations but it has a little difference with Al-Kattan correlation (2015), (Fig. 15).

Fig.15. Comparison between equation 14 and other empirical relation to predict Vs. for dolomite rock formation from core data

The new correlation is matched the Ameen (2009) and Castagna (1993) correlations but less relative matching with the Kattan correlation (2015). The new correlation gives an excellent matching with Ameen (2009) and Castagna (1993) correlations but have some differences with Kattan correlation (2015) (Fig. 17).

Fig.16. Comparison between equation 13 and other empirical relation to predict Vs. for limestone rock in the Khasib Formation from log data

Fig. 17. Comparison between equation 14 and other empirical relation to predict Vs. for dolomite rock formation from log data

5. Conclusions

This study presents a set of correlations to estimate the rock mechanical and elastic properties based on lab experimental works using the multiple regression analysis technique. A field case (FAUQI oil field), located in southeast Iraq, was conducted to correlate the rock mechanical with petrophysical properties. The greatest difference between this study and previous studies is that there are no local studies to estimate the rock mechanical properties in this field of interest. The conclusion of this study can be summarized in the following points:

- Petrophysical rock properties including porosity, compressional shear waves, and bulk density are consistent indexes to estimate the rock mechanical properties.
- The results are more conservative in estimating UCS rather than using previous correlations.
- The results of Vs and Vp are well matched with log data when the core plugs are saturated with diesel oil than when the core plugs are dried.
- The presented correlations can be used to estimate UCS, Vs, and Vp from well log data if the core samples are limited or not available, which is a cost effective correlation.
- Even though all of Vs correlations (previous and developed) show a good match with well log data, their prediction ability is different. For example, Castagna and Ameen correlations show a closely match with the developed correlations while Alkattan correlation showed an overestimation of Vs magnitudes.
- The developed correlations in this study can be locally used with high performance capacity, but it requires a calibration when it will be used in another field of interest.

Nomenclature

UCS: uniaxial compressive strength

Vp: compressional wave

Vs: shear wave

Es: young modulus

UV: ultrasonic velocities

ASTM: American Society for Testing and Materials

ISRM International Society for Rock Mechanics

Acknowledgements

The authors are very grateful to the Editor in chief Prof. Dr. Salih M. Awadh, the Secretary of Journal Mr. Samir R. Hijab. and the Technical Editors for their great efforts and valuable comments.

References

- Abdul Majeed, R. K., Alhaleem, A. A., 2020. Estimation of shear wave velocity from wireline logs data for Amara oil field, Mishrif Formation, southern Iraq, *Iraqi Geological Journal*, 53(1A), 36-47.
- Al-Kattan, W., Al-Ameri, N.J., 2015. Estimation of the rock mechanical properties using conventional log data in North Rumaila Field. *Iraqi Journal of Chemical and Petroleum Engineering*. 13 (4), 27-33.
- Ameen, M. S., Smart, B. G., Somerville, J. M., Hammilton, S., Naji, N. A., 2009. Predicting rock mechanical properties of carbonates from wireline logs; A case study; Arab-D reservoir, Ghawar field, Saudi Arabia. *Marine and Petroleum Geology*, 26(4), 430-444.
- ASTM, 1986. Standard Test Method of Unconfined Compressive Strength of Intact Rock Core Specimens. ASTM Publication.
- Bjorlykke, K., Hoeg, K., 1997. Effects of burial diagenesis on stresses, compaction, and fluid flow in sedimentary basins. *Marine and Petroleum Geology* 14, 267–276.
- Castagna, J. P., Batzle, M. L., Kan, T. K., 1993. Rock physics - The link between rock properties and AVO response. In: Offset-dependent reflectivity-theory and practice of AVO analysis: Castagna, J.P., and Backus, M. (Eds.). Society of Exploration Geophysicists, 135–171.
- Chang, C., Zoback, M.D., Khaksar, A., 2006. Empirical relations between rock strength and physical properties in sedimentary rocks. *Journal of Petroleum Science and Engineering*, 51(3), 223-237.
- Hadi, F. A., and Nygaard, R., 2018. Shear wave prediction in carbonate reservoirs can Artificial neural Network outperform regression Analysis? In 52nd US Rock Mechanics, Geomechanics Symposium. American Rock Mechanics Association.
- ISRM, 2007. The Complete ISRM Suggested Methods for Rock Characterization. Testing and Monitoring: 1974-2006. International Society for Rock Mechanics, Commission on Testing Methods.
- Karamia, M., Abrah, B., Dayani, S., Faramarzi, L., Nik, M. G., 2012, January. Empirical correlations between static and dynamic properties of intact rock. In ISRM Regional Symposium-7th Asian Rock Mechanics Symposium. International Society for Rock Mechanics and Rock Engineering.
- Khandelwal, M. S., Singh, T.N., 2009. Correlation static properties of rock with P-wave velocity international Journal of Coal Geology, 49 (1), 55-60.
- Meehan, N.D., 1994. Rock mechanics issues in petroleum engineering. In: Nelson, P.P., Lauback, S.E. (Eds.), *Rock Mechanics*. Balkema, Rotterdam.
- Militzer, H., Stoll, R., 1973. Einige Beiträge der Geophysik zur Primärdatenerfassung im Bergbau: *Neue Bergbautechnik*. Leipzig, 3, 21-25.
- Raaen, A. M., Hovem, K. A., Joranson, H., and Fjaer, E., 1996. FORMEL: A Step Forward in Strength Logging. In Proceedings of the SPE Annual Technical Conference and Exhibition, Denver, Colorado.
- Rabbani, E., Sharif, F., Koolivand Salooki, M., Moradzadeh, A., 2012. Application of neural network technique for prediction of uniaxial compressive strength using reservoir formation properties. *International Journal Rock Mechanics and Mining Society*, 56, 100-111
- Tawfeeq, Y. J., Al-Sudani, J. A., 2020. Digital rock analysis: an alternative method to predict petrophysical properties, case study from Mishrif Formation. *Iraqi Geological Journal*, 53(2C), 34-55.
- Smorodinov, M. I., Motovilov, E. A., Volkov, V. A., 1970. Determination of correlation relationships between strength and some physical characteristics of rocks, *Proceeding of the Second Congress of the International Society for Rock Mechanics*, Beograd, 21-26.
- Yagiz, S., 2011. P-wave velocity test for assessment of geotechnical properties of some rock materials. *Bulletin Material Society*, 34 (4), 947-953.