Petroleum and Coal

Article **Open Access**

Laboratory-Based Correlations to Estimate Geomechanical Properties for Carbonate Tight Reservoir

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Received January 3, 2022; Accepted May 23, 2022

Abstract

Rock mechanical properties are critical parameters for many development techniques related to tight reservoirs, such as hydraulic fracturing design and detecting failure criteria in wellbore instability assessment. When direct measurements of mechanical properties are not available, it is helpful to find sufficient correlations to estimate these parameters. This study summarized experimentally derived correlations for estimating the shear velocity, Young's modulus, Poisson's ratio, and compressive strength. Also, a useful correlation is introduced to convert dynamic elastic properties from log data to static elastic properties. Most of the derived equations in this paper show good fitting to measured data, while some equations show scatters in correlating the data due to the presence of Calcite, Quartz, and clay in some core samples. Brittleness index (BRI) indicates ductile behavior of the core samples is also studied for the interested reservoir. The results of BRI show that the samplers range from moderate to high brittleness, and the difference in BRI comes from the presence of some minerals, as explained using the X-ray diffraction test (XRD). The proposed correlations are compared to other correlations from literature for validation, and the results of the comparison show good matching that explains the accuracy of the proposed equations.

Keywords: *Static elastic properties; Dynamic elastic properties; Brittleness index; X-ray diffraction test (XRD); Compressive strength; Experimentally-derived correlations.*

1. Introduction

In recent studies, geomechanical properties are important parameters to eliminate many problems in the oil industry. For instance, estimating geomechanical properties during drilling can reduce wellbore instability by providing the failure criteria around the wellbore [1-2]. Wellbore instability problems can be reduced significantly when the study is related to wellbore stability changes during reservoir depletion [3-5]. Other problems related to well drillings, such as sand production, can be eliminated by accurately determining geomechanical properties [6-7]. Relating geomechanical properties to hydraulic fracturing propagation is another essential study proposed by many authors such as Huang *et al.* [8]and Al-Dossary *et al.*,[9].

In unconventional reservoirs, the importance of implicating geomechanical studying in production and development stages becomes essential. Developing a tight reservoir required specific strategies due to the ultralow permeability of these reservoirs.

Laboratory-based determination of geomechanical properties is the accurate method to use, even though it is expensive and time-consuming. When the core samples for the depth of interest are not available for testing, it is recommended to derive empirical correlations from the available core samples measurements. The obtained correlations will be beneficial to find geomechanical properties such as Poisson's ratio (ʋ), Young's Modulus (E), and compressive strength (CS). Another essential step after geomechanical properties measurements is to derive an equation that relates the dynamic and static properties [10-12]. Developing such direct correlations between dynamic and static geomechanical properties can effectively estimate mechanical properties from log data in the depth of lacking measurements.

This study uses geomechanical and physical properties measurements of 12 core samples to find significant experimentally derived correlations for a carbonate reservoir. These derived equations are essential in drilling, hydraulic fracturing, and enhancing recovery for the tight reservoir under study. Also, the obtained relations were compared to other relations reported in the literature to explain the validity of the derived correlations.

2. Samples properties

In the current study, 12 core samples are collected from three wells (wells B, C, and V5X) passing through the studied carbonate reservoir and the samples cover the main sections of the reservoir. The reservoir consists of two main layers: A and B layers. A layer consists of mud lime without hydrocarbon shows. While the B layer is a hydrocarbon show, its estimated initial oil in place (IOIP) represents 25% of the total IOIP in the studied field. The layer B consists of three main layers, which are B1, B2, and B3.

The primary lithology of B1 layer is bioturbated wackestone, while the B2 layer comprises primarily bioturbated packstone and pelagic foram chondrites, which are either dolomitized or pyrite cemented. The B3 layer has developed shale containing smectitic, pyrite, oolitic packstone, skeletal intraclasts packstone; echinoderms, pebbles, oolitic, and dark grain (pyritic), and chondrite can also be found in the layer B3.

The depths, geomechanical, and petrophysical properties measurements of the core samples are listed in Table 1. The sample's physical properties include compressional velocity (Vp), shear velocity (Vs), bulk density (ρ_b), and porosity (φ). The geomechanical properties of the samples are also listed in table-1, including Poisson’s ratio (υ) and Young’s modulus (E) measurements in both static and dynamic methods (ultrasonic test). All the testing methods and the proposed formula for the determination of mechanical properties for the core samples are mentioned by [13]. The laboratory results data listed in Table 1 will be used to find general correlations between physical and geomechanical properties for studied reservoir.

Table 1. Core samples properties and depth

	Sample no./layer	Depth m	ρ_b gm/cc	Porosity%	E_s, Gpa	υ_s	υ_d	E_d, Gpa	C.S., Gpa	V_S, m/s	V_P m/s
Well B	1/S-B1	2673	2.67	18.73	19.98	0.330	0.25	15.568	73.509	3149	3643.6
	2/S-B2	2694	2.67	23.4	17.23	0.257	0.25	19.099	57.871	3148	3644
	3/S-B3	2711	2.68	24.58	5.406	0.157	0.25	14.129	52.402	3143	3636
Well C	4/S-B1	2735	2.66	15	12.92	0.257	0.25	12.818	70.575	2936	3400
	5/S-B2	2762	2.66	20.7	12.28	0.242	0.25	15.382	58.224	2935.7	3402
	6/S-B3	2796	2.71	19.8	5.056	0.255	0.25	11.699	42.345	2930	3392
Well V5X	7/S-B1	2686.33	2.66	19.21	18.04	0.27	0.29	19.00	173.94	3202	3722
	8/S-B1	2680.68	2.66	19.21	12.83	0.28	0.29	13.00	163.96	3205	3720
	9/S-B2	2701.71	2.65	25.5	13.88	0.28	0.29	13.00	141.39	3193	3614
	10/S-B2	2722.66	2.66	23.7	15.98	0.30	0.32	18.00	188.43	3190	3611
	11/S-B3	2725.33	2.68	25.78	7.91	0.22	0.25	10.00	130.19	3190	3620
	12/S-B3	2728.07	2.68	25.6	5.35	0.14	0.25	10.00	118.86	3190	3622

3. Empirical equations

Two general methods are known to evaluate rock mechanical properties. One method involves estimating stress-strain behavior by applying different load range on a rock sample. This method allows for measuring the static elastic properties of the formation. The other method involves measuring both compressional and shear wave propagation velocities used to estimate dynamic rock elastic properties using fundamental relations. In obtaining these relations, samples of high clay content will be neglected to reduce the misfit in data plotting and obtain a systematic equation to represent the required relations. This section will illustrate the main outlines for adopting these two methods for the reservoir under study.

3.1. Relation between compressional and shear velocity

Figure 1 shows the linear relation between the compressional and shear velocity of the carbonate 12 samples. The obtained equation's high correlation factor (0.9936) reveals the strong relationship between the two velocities. The obtained equation is given below:

$V_s = 0.8222V_p + 142.84$ (1)

Due to the absence of shear velocity in conventional logging data, the obtained experimentally derived equation can be beneficial to approximate the shear velocity of the reservoir at any depth.

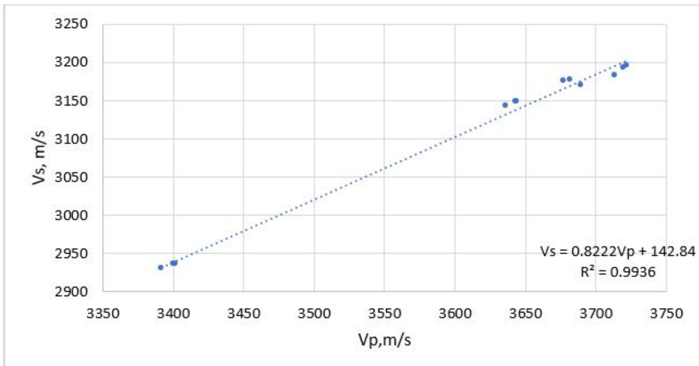

Figure 1. Relation between compressional and shear velocity

3.2. Estimating dynamic mechanical properties and conversion from dynamic to static elastic properties

Young's modulus and Poisson's ratio indicate rock deformation. When the estimated Young's modulus is high and Poisson's ratio is low, then this formation is more rigid. The dynamic Young's modulus and Poisson's ratio are usually derived from well logs and are calculated using the measured V_p and V_s as follows:

$\upsilon_d=(V_P^2-2V_S^2)/2(V_P^2-V_S^2$ (2)

$E_d=[\rho_b\ V_S^2(3V_P^2-4V_S^2)/(V_P^2-V_S^2)]$ (3)

where E_d=dynamic Young's modulus; ρ_b =density (g/cm^3); V_s=Shear wave velocity (m/s); V_p=compressional wave velocity (m/s), and υ= Poisson's ratio.

Figure 2 explain the linear relation between static and dynamic Poisson's ratio and the relation between static and dynamic Young's modulus. The following equations are obtained from linear elastic properties relation of the studied reservoir:

$E_s = 1.3244E_d - 7.4154$ (4)

$\upsilon_s= 1.2\upsilon_d- 0.076$ (5)

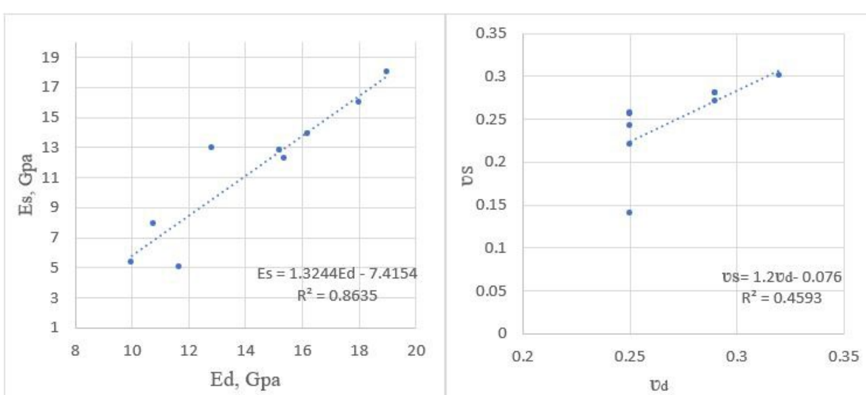

Figure 2. Relation between static and dynamic mechanical properties

The static elastic modulus is the most important in rock mechanics because it reveals rock deformation under high applied stress. Sometimes it is not easy to conduct a laboratory measurement to obtain static properties. Therefore, these correlations are essential to convert dynamic Young modulus and Poison's ratio to approximated static Young modulus and Poison's ratio.

3.3. Obtaining compressive strength correlations

The compressive strength (CS) of a rock can be measured directly in the laboratory. This parameter indicates rock hardness. Experimental measurements of CS represent the maximum load that the sample was subjected to before fracturing. Compressive strength can be calculated using velocity or mechanical properties. Compressional velocity, shear velocity, and Young modulus listed in the Table 1 have been used in this paper to estimate compressive strength. Figure 3-a demonstrates a positive relation between compressional velocity and compressive strength.

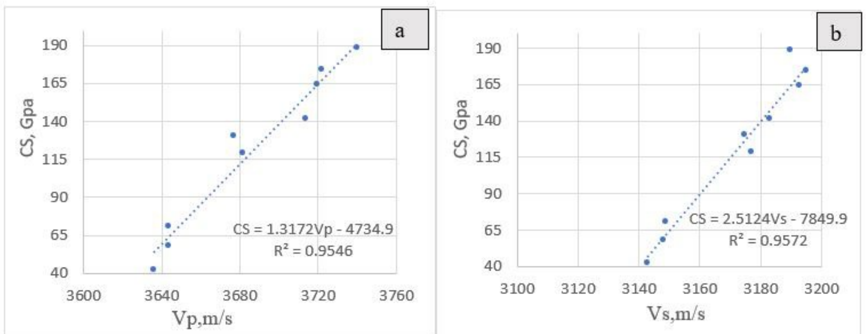

Figure 3. Relation between compressional, shear velocity, and compressive strength

In contrast, Figure 3-b illustrates the positive relation between shear velocity and compressive strength. The obtained relationships have an excellent fitting and are very useful to find CS for different ranges of both shear and compressional velocities values. The obtained correlations are given in the following equations:

$$CS = 1.3172V_p - 4734.9 \quad (6)$$

$$CS = 2.5124V_s - 7849.9 \quad (7)$$

The relationship between compressive strength CS and Young's modulus for the studied reservoir is illustrated in Figure 4. The data are scattered, and it is challenging to obtain a relation between compressive strength CS and Young's modulus.

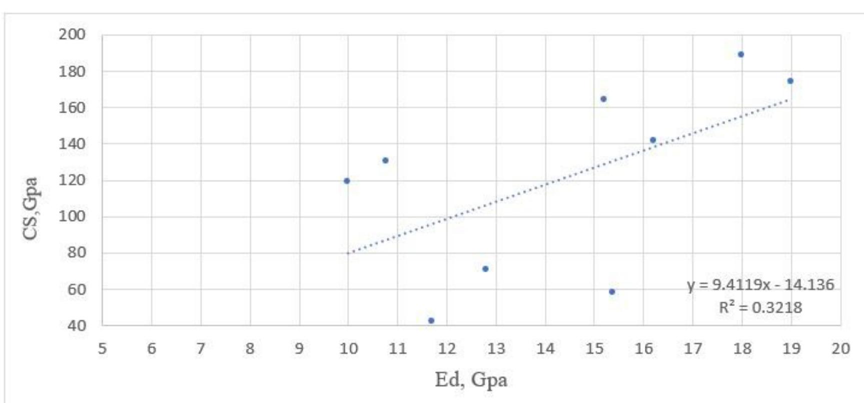

Figure 4. Relation between dynamic Young's modulus and compressive strength

In practice, using Young's modulus to estimate compressive strength is not straightforward. Therefore, the obtained relation will be either overestimate or underestimate the CS, while using compressional or shear velocity to estimate CS is a direct relation. The scatter shown in Figure 4 for the estimated CS can be attributed to the diagnosis process of some core samples such as calcite, quartz, and cement. These minerals are found in the studied core samples due to the X-ray diffraction (XRD) test conducted for the 12 core samples. According to the XRD test of the core samples, the calcite percentage is higher, and it ranges from 76.2% to 90% of the total sample mineral.

On the other hand, the total clay is the second higher mineral percentage after calcite, and it ranges from 7.3% to 15.2% of the total mineral content according to the XRD test. In contrast, Quartz represents the third higher third mineral content in the interested samples within a range of 4.24% to 5.5%. The presence of these minerals within a higher percentage in the core samples effects on core's porosity and the accuracy of log data of these cores. This mineral effect on samples' porosity will affect the calculated dynamic Young's modulus. Therefore, the resulting relation between CS and Ed has not fit the data.

The same mineral content range and types (calcite, quartz, and cement) in the core samples cause a wide scattering when finding a relation between compressive strength CS and cores porosity. Figure 5 shows such high data scattering and suggests that porosity alone is not a good indicator for compressive strength estimation. The difficulties in finding a beneficial relationship between rock compressive strength and porosity are also mentioned by [14]. The author indicates that the most empirical equations relating to rock physical properties and strength do not fit the measured data.

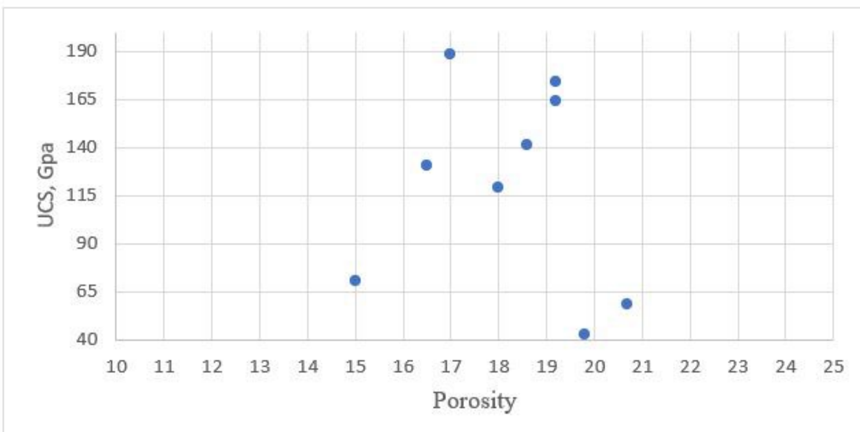

Figure 5. Relation between core porosity and compressive strength

3.4. Rock brittleness calculation

Tight reservoir development needs specific strategies. One of the typical strategies to increase tight reservoirs recovery is hydraulic fracturing. In hydraulic fracturing operations, rock brittleness is a vital parameter to reflect the ability of the rock to create fractures. If the rock is brittle, then long fractures are expected. The ductile behavior of the rock indicates the difficulty of inducing hydraulic fracturing.

In general, brittleness can be affected by the lithology of the rock, especially quartz and clay content [15]. Another critical parameter affecting the degree of rock brittleness is the rock elastic properties. Rock's high brittleness indicates high Young's modulus and low Poisson's ratio. In this study brittleness index for the studied core samples are calculated based on both Young's modulus and Poisson's ratio [16] as follows:

$$BRI\_E = \frac{E-E_{min}}{E_{max}-E_{min}} * 100 \quad (8)$$

$$BRI\_\upsilon = \frac{\upsilon-\upsilon_{max}}{\upsilon_{min}-\upsilon_{max}} * 100 \quad (9)$$

$$BRI\_avg = 0.5*(BR\_E+BR\_\upsilon) \quad (10)$$

where: BRI_E: brittleness index based on Young's modulus; E: measured value of Young's modulus, GPa; E_min: minimum value of Young's modulus, GPa; E_max: maximum value of Young's modulus, GPa; BRI_ʋ: brittleness index based on Poisson's ratio; ʋ: measured value of Poisson’s ratio; υ _max: maximum value of Poisson’s ratio; υ _min: minimum value of Poisson’s ratio; BRI_avg: brittleness index based on Young's modulus and Poisson's ratio.

For the studied core samples, the calculated brittleness index (BRI) and its relation to elastic properties are illustrated in Figure 6-a. A perfect relation is obtained to find BRI in terms of Poisson's ratio using the following equation:

$$BRI = -526.32\,\upsilon + 173.68 \qquad (11)$$

On the other hand, no relation is obtained to estimate rock brittleness in terms of Youn's modulus, as shown in Figure 6-b. Grieser *et al.*, [17] stated that if the brittleness index is higher than 40, the rock could be considered brittle, and if the value is higher than 60, then the rock is very brittle.

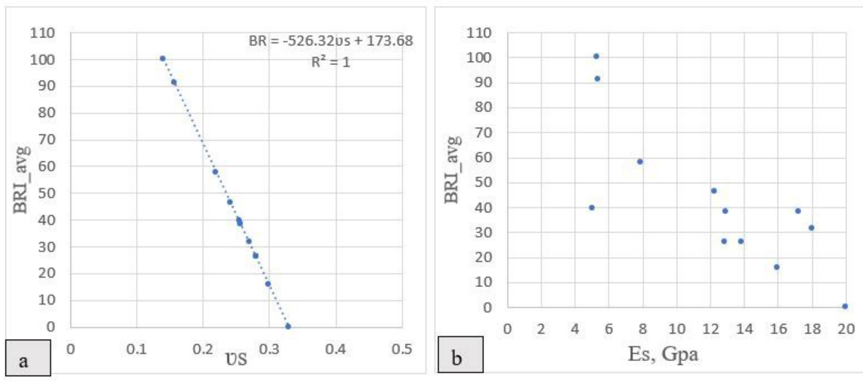

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Figure 6. Relation between core brittleness and elastic properties

4. Case study and validation of the new correlation

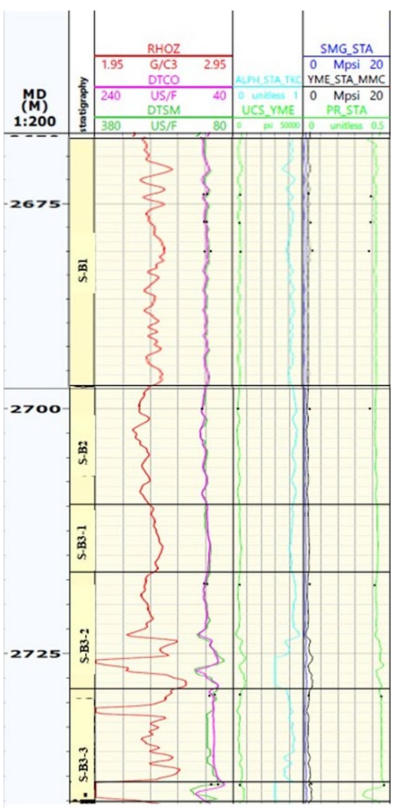

Figure 7. Calculated and measured mechanical properties

The well log data from well B were used for estimating mechanical properties for the reservoir using the proposed correlations in the current study. Figure 7 shows the compressional transit time log from well B. The shear transit time is not available for this well, so equation 1 is used to obtain shear velocity and convert it to shear transit time. The results of calculating shear transit time are drawn in Figure 7. The measured shear and compressional time data from Table 1 are also drawn in Figure 7 as dot points to explain the validation of the used equation. Then these two velocities are used to calculate both dynamic Young’s modulus and dynamic Poisson’s ratio using equations 2 and 3, respectively. The new derived correlations (equations 4 and 5) are then used to convert the dynamic elastic properties to static ones, and the results are shown in Figure 7. The measured Young modulus and Poisson’s ratio are also drawn in Figure 7 to illustrate the accuracy of equations 4 and 5 in dynamic to static conversion of elastic properties.

The compressive strength is calculated for well B using the new correlation derived in the current study. Using shear and compressional velocity, equations 6 and 7 are used to obtain the compressive strength. The calculated compressive strength and the measured CS from Table 1 are drawn in Figure 7 to illustrate the high accuracy of the new correlations.

Another critical step is to check the accuracy of the proposed correlation by comparing the new correlation (reservoir correlation) results to the available correlations in the literature. Equation 1 for estimating the correlation between Vs and Vp for S-reservoir is compared with Castagna correlation and Ameen *et al.* correlation since these correlations are given for the same lithology of carbonate S-reservoir. Castagna correlation is given in equation 12 [18], and Ameen *et al.*, [19] correlation are given in equation 13.

$$V_S = 0.4403V_P + 0.576 \quad (12)$$

$$V_S = 0.52V_P + 0.25251 \quad (13)$$

The results of the comparison of the three equations are shown in Figure 8 to indicate an accepted result of the proposed new correlation. The difference in using current correlations (equation 1) and other correlations (equation 12 and 13) for the same carbonate reservoir is expected. This difference is due to the difference in formations porosity between the low porosity of tight reservoir samples and the sample's higher porosity of other correlations.

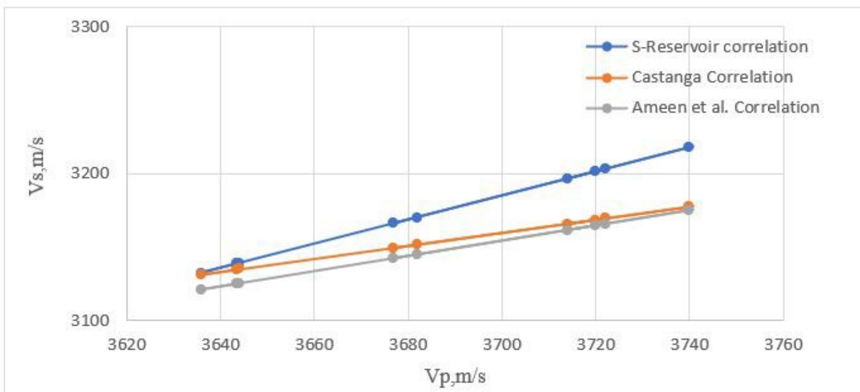

Figure 8. Comparison of Vs and Vp correlations

The new correlation of estimating rock compressive strength introduced in equation 6 using compressional velocity Vp is compared with the correlation proposed by Militzer and Stoll [20] as given in equation 14. The results of Equations 6 and 14 are shown in Figure 9.

$$CS = 2.45V_P^{1.92} \quad (14)$$

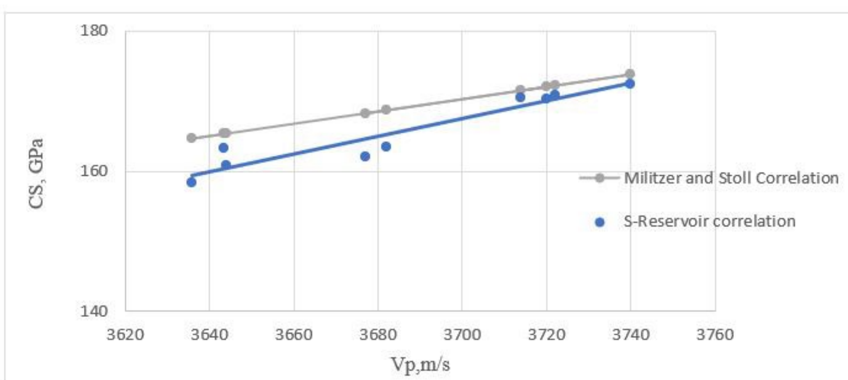

Figure 9. comparison of compressive strength correlations

5. Conclusions

Measured mechanical properties were used in the current study to obtain important correlations, which can be used for other carbonate reservoir. The proposed equation works well in fitting the measured data to estimate reservoir mechanical properties. Scatter in some relations in obtaining good fitting to measured data comes from certain minerals in core samples. It is essential to mention that the obtained correlations are proposed for low porosity- low permeability samples, so caution should be taken when comparing the new correlations to other correlations.

The brittleness index is calculated based on Young's modulus and Poisson's ratio. The calculated brittleness index is an essential tool to estimate rock's ability to fail without compressive strength measurements. A perfect relation is obtained to find BRI in terms of Poisson's ratio while no relation is obtained to relate BRI to Young modulus.

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