The effect of rock types on pore volume compressibility of limestone and dolomite samples

Aloki Bakhtiari H.[1*], Moosavi S.A.[2], Kazemzadeh E.[1], Goshtasbi K.[2], Esfahani M.R.[1], Vali J.[1]
[1]*Core Lab, Research Institute of Petroleum Industry, Tehran, Iran*
[2]*Rock Mechanics Division, Faculty of Engineering, Tarbiat Modares University, Tehran, Iran*
**Corresponding author,e-mail:* Bakhtiarih@ripi.ir
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Abstract

Determination of porosity, permeability, and pore volume compressibility of reservoir rocks and those variations with effective stress changes are of great interest in petroleum engineering. This paper has studied the influence of pore types of carbonate reservoir rocks on pore volume compressibility as well as Klinkenberg permeability and porosity at different stress values. In the current study pore volume compressibility tests have been done on 38 limestone and 8 dolomite samples. The experiments show the importance of rock type description of the reservoir rocks. Carbonate rocks with touching vug pores have different behavior from the other studied carbonates in this paper. This complex behavior is related to the role of connecting paths closure on the characteristics of hydraulic conductivity of the rock while there is no more changes in porosity or volume change. It means that the planar connecting paths have more effect on hydraulic conductivity of this rock type, while it has not more effect on porosity. Also, in all rock types excluding touching vuggy pores limestone, increasing the initial porosity leads to increase the permeability at the same effective stress value.

Keywords: *Pore Types, Pore Volume Compressibility; Porosity; Permeability; Effective Stress.*

Introduction

Hydrocarbon production from a reservoir increases the effective stress, which causes a reduction of the reservoir pore volume compressibility as well as porosity and permeability, and consequently a reduction in the production rate (Zheng, 1993). There are three types of rock compressibility: pore volume compressibility, bulk compressibility and grain compressibility. The importance of pore volume compressibility instead of the other rock compressibilites is related to the fact that rock compressibility is a combination of grain compressibility and pore structure changes, where grain compressibility during hydrostatic stress condition is negligible (Zheng, 1993). Rock type and pore structures play a key role in determining the behavior of the reservoir rocks during the hydrocarbon production, causes to decrease in pore pressure which accordingly increases effective stress.

The effect of effective stress on porosity and permeability as well as rock compressibility has been investigated by some researchers (Rhett and Teufel, 1992; Ghabezloo *et al*., 2009; Dong *et al*., 2010; Medina *et al*. 2011). They showed that the hydrological properties of reservoir rocks are sensitive to variations of the effective stress. Initially, (Terzaghi, 1936) introduced the effective stress concept as the difference between the total stress and pore pressure which is widely used in Geoengineering problems. After that, the effective stress concept has been modified by Biot (1941 and 1957).

(Rhett & Teufel, 1992) studied the effect of stress path on permeability and compressibility of sandstones. They concluded that, the increase of permeability at low stress ratios is greater than the increase of permeability at hydrostatic stress condition (stress ratio=1). But they could not explain the responsible mechanism. (Zheng, 1993) indicated that compressibility at low stress values is more sensitive to stress and it is due to the closure of highly compliant pore spaces. (Han & Dusseault 2003) have worked on the stress-dependent porosity and permeability of weakly consolidated sandstone applied to an oil production wellbore. They concluded a good nonlinear theory for weakly consolidated sandstones. Also, (Iscan *et al*., 2006) estimated the effect of confining pressure on permeability of limestone from southeast Turkey. They correlated a descending power fit on their experimental data. Also, (Luo & Feng, 2009) studied the effect of confining pressure on deformation characteristics of low permeability rocks. They used a rock mechanics apparatus to measure rock compressibility along with mercury injection method and cast thin section identification to study the deformation characteristics of low permeability and tight reservoir rocks. They concluded that, due to high clay and cement content and narrow pore throat, the deformation process of low permeability rocks is not perfectly elastic. Therefore, the stress sensitivity of low permeability rocks is more than that of high permeability medium. Furthermore, (Ghabezloo *et al*., 2009) performed some experiments on effective stress law for the permeability of a limestone. They mentioned that the variation of the permeability due to change in the pore pressure is more important than the confining pressure change. They proposed a power law variation of the permeability with the effective stress.

Early studies on rock compressibility are related to the works done by Hall (1953), Geertsma (1957), Fatt (1958), Kracher and Schöpf (1973) and Newmann (1973). Although, these studies started at 1950, however, still there is not a comprehensive study on the impact of rock type on pore volume compressibility of the reservoir rocks.

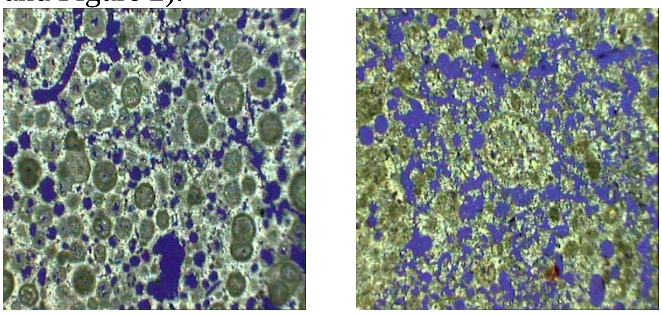
In this paper rock typing is preformed based on thin section studies of two sample sets; dolomite and limestone. Later, we have worked on the effect on pore types on the compressibility of these rocks, which have not been yet done. Therefore, the relationship between effective stress and porosity, permeability and pore volume compressibility will be investigated. Also, we have worked on the effect of stress on the permeability-porosity relations. But the emphasis of this study is to investigate the effect of pore types on pore volume compressibility. For this purpose, pore volume compressibility tests were done on 38 samples of limestone and 8 samples of dolomite by CMS-300 method and the porosity and Klinkenberg permeability of the samples were measured at different stress values, simultaneously. In this way, the correlation of pore volume compressibility versus effective stress is assumed to be an exponential form of (Liu *et al*., 2009):

$$C_{pc} = C_{\mathrm{pc}}^{\infty} + a \exp\left(\frac{-\sigma}{b}\right) \quad \textbf{(1)}$$

where and are constants. and are pore volume compressibility and effective stress, respectively. Also, is pore volume compressibility at high effective stress level, which can be determined by the equation of horizontal asymptote of the pore volume compressibility-stress curve. Therefore, an empirical curve-fitting procedure is used to determine the coefficients of Eq. (1), which for all samples gives satisfactory estimations.

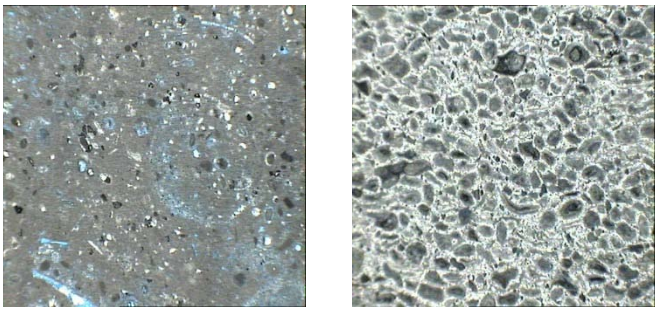
Pore Type Description

In the study, rock typing is done based on thin section studies. Three types of limestone and two types of dolomite were grouped according to Lucia (2007); crystalline limestone, separated vuggy pores limestone, limestone with intermediate to well-connected or touching vuggy pores, mud-dominated dolomite and grain-dominated dolomite (Figure 1 and Figure 2).



(a) (b)

Figure 1: Limestone thin sections; (a) separated vuggy pores limestone and (b) well-connected vuggy pores limestone.



(a) (b)

Figure 2- Dolomite thin sections; (a) mud-dominated dolomite and (b) grain-dominated dolomite.

Figure 1. (a) depicts an example of a separated vuggy limestone. As shown in the figure the pores

are not connected to each other. They are weakly connected through the interparticle pore spaces. Although the addition of separate vugs increases total porosity, it does not significantly increase permeability. Therefore, permeability of limestones with little vugs or non-vuggy porosity is a function of interparticle porosity, grain size and sorting. An example of a touching vuggy limestone is shown in Figure 1. (b). Rock sample with touching vugs has pore spaces, which are significantly larger than the particle size and forms an interconnected pore system. Figure 2 shows an example of two classified dolomites including mud-dominated (a) and grain-dominated (b) dolomite.

Test procedure

The samples were plugs of 1.5 inches in diameter and 2 inches height drilled from carbonate reservoir rocks. The samples were placed into a Soxhlet extraction apparatus for cleaning, and then drying were performed in an oven at temperature of 60^{o}C for a period of 48 hours.

Compressibility tests were performed using CMS-300 equipment, while the stress has changed at 4 or 5 rising steps discontinuously. CMS-300 is able to calculate the pore volume compressibility at different hydrostatic stress conditions as well as measuring porosity and permeability. In these experiments porosity and pore volumes obtained from the equipment at each effective stress increasing intervals. Porosities were measured by injection of Helium gas, which employs Boyle's law, where the helium gas in the reference cell isothermally was expanded into the sample cell. After expansion, the resultant equilibrium pressure was measured to obtain the porosity. Also, Klinkenberg permeabilities of all samples have measured by the equipment, simultaneously. The maximum stress value was set to 6000 psi.

Experimental results

Eq. (1) has a very good fitted correlation with experimental data. For example Figure 3 shows the correlation for 4 crystalline limestone samples. One can see from the figure that pore pressure drawdown, which causes to increase effective stress, decreases pore volume compressibility.

Table 1 shows the coefficients of the fitted theoretical relation (Eq. (1)). To represent the normalized measure of the strength of linear relationship between variables the correlation coefficient matrix is suitable.

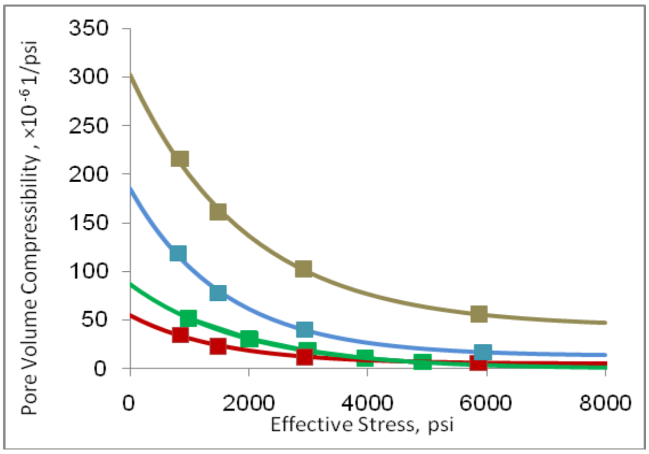


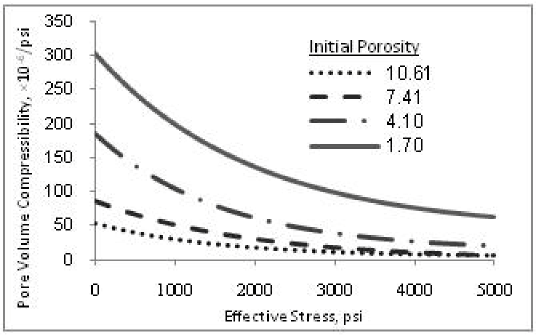
Figure 3: An example of compressibility-stress curves for 4 samples of crystalline limestone, dashed lines are theoretical fitted correlation and cubic marks represent experimental data.

Therefore, after looking forward to the relation between initial porosity and coefficient a – which is equal to initial compressibility – we found that, there is a strong negative linear correlation between each pair of initial porosity data and coefficient a in the crystalline and separated vuggy pores limestones. It means that the initial porosity data have a negative linear relationship with the coefficient a in the crystalline and separated vuggy pores limestones. But this situation is not observed in touching vuggy pores limestones; i.e. there is no linear relationship between the data couples of the initial porosity and the coefficient a for this category. Still, in the touching vuggy pores limestone there is a negative correlation between the initial porosity and the coefficient a to some extent. The correlation between compressibility and initial porosity data reported in this paper is similar to the conclusion reached by other researchers (Liu *et al.*, 2009; Hall, 1953; Jalalh, 2006). However, there is a contrary condition in grain-dominated dolomites in which we have seen a positive linear correlation between initial porosity and coefficient a, which is in contrary to previous studies. Therefore, as result of limited range of initial porosity it does not seem to be a reasonable result. Furthermore, due to the lack of data in mud-dominated dolomites and also the analogous initial porosity measures of these few data, the correlation between the data pairs is not treatable. Although there is no evidence of any clear linear correlation between the initial porosity and the other coefficients; C_{pc}^{∞} and b, it has observed a negative correlation between the initial porosity and these two coefficients to some extent.

Table 1: Coefficients of fitted correlation in different rock types(A: crystalline limestone, B: separated vuggy pores limestone, C: touching vuggy pores limestone, D: mud-dominated dolomite and E: grain-dominated dolomite.)

Rock Type		Sample No.	Initial Porosity %	$C_{pc}^{\infty} \times 10^{-6} psi^{-1}$	$a \times 10^{-6} psi^{-1}$	b psi
Limestone	A	6V	7.41	0.324	86.62	1923
Limestone	A	259H	10.61	4.50	49.97	1548
Limestone	A	203H	4.1	12.85	172.31	1580
Limestone	A	146H	1.7	42.75	260.24	1968
Limestone	B	4H	23.94	0.12	41.26	1816
Limestone	B	6H	19.09	0.70	95.03	2219
Limestone	B	26H	22.49	0.12	68.46	1355
Limestone	B	14H	24.93	0.16	44.67	1704
Limestone	B	10H	24.3	0.31	29.40	2504
Limestone	B	4V	28.39	0.17	30.98	2102
Limestone	C	36H	26.45	0.14	28.46	1847
Limestone	C	40H	23.88	3.19	47.12	1313
Limestone	C	1H	24.65	0.01	29.91	2697
Limestone	C	20H	20.47	0.15	24.61	2096
Limestone	C	26H	19.81	4.11	31.37	1444
Limestone	C	29aH	23.93	3.75	46.63	1337
Limestone	C	29bH	18.18	0.13	45.88	1620
Limestone	C	2H	21.64	4.90	40.40	1403
Limestone	C	7aH	13.79	0.75	38.04	3366
Limestone	C	16H	10.64	0.38	39.12	2436
Limestone	C	4H	25.37	3.80	26.17	1464
Limestone	C	5H	11.16	0.16	30.47	2142
Limestone	C	6H	19.80	0.03	92.47	937
Limestone	C	7H	23.34	0.22	36.04	1973
Limestone	C	8H	16.00	0.20	32.14	2157
Limestone	C	8V	21.58	0.18	25.27	2389
Limestone	C	10H	20.82	2.66	31.82	1334
Limestone	C	10V	23.19	3.80	27.60	1453
Limestone	C	11H	27.16	2.49	22.32	1395
Limestone	C	13H	23.40	0.14	52.21	1606
Limestone	C	13V	26.12	4.8	34.01	1605
Limestone	C	16V	21.83	0.03	77.12	939
Limestone	C	17H	22.30	0.07	39.35	1409
Limestone	C	18H	28.24	0.24	34.18	2272
Limestone	C	19V	23.83	3.31	23.15	1565
Limestone	C	20H-2	21.54	0.05	51.61	1260
Limestone	C	21H	23.66	2.76	22.43	1409
Limestone	C	22H	18.92	0.09	74.49	1276
Dolomite	D	26V	8.31	0.17	36.44	1922
Dolomite	D	36V	8.42	3.36	26.83	1424
Dolomite	E	28V	20.69	0.11	18.94	2293
Dolomite	E	29V	20.10	0.18	12.81	2337
Dolomite	E	29H	21.29	0.19	21.40	2609
Dolomite	E	32H	17.09	0.30	14.27	3713
Dolomite	E	34H	19.37	0.09	18.09	2103
Dolomite	E	37H	22.18	0.01	50.54	946

Figure 4 depicts the relationship between pore volume compressibility and effective stress for different rock types at different initial porosities. As it is obvious from the figure, crystalline and separated vuggy pores limestones and mud-dominated dolomites represent a clear trend at different initial porosities. It can be mentioned that the pore volume compressibility curves move down by increasing the initial porosity. However, there isn't such a behavior in the other rock types here. The touching vuggy pores limestone has an irregular trend at different levels of initial porosities, especially at higher values of initial porosities. In addition, as mentioned before, in these experiments there is an inverse trend in grain-dominated dolomite, i.e. by increasing the initial porosity of the rock the pore volume compressibility increases.



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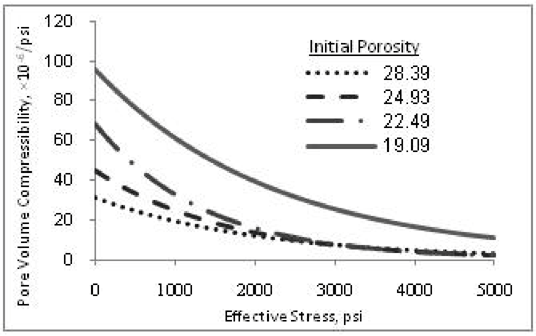

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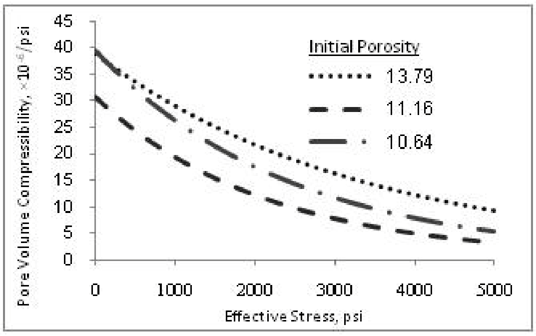

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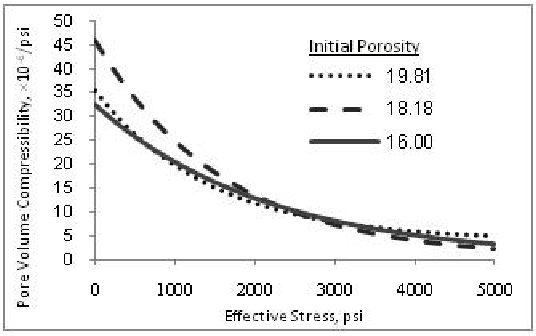

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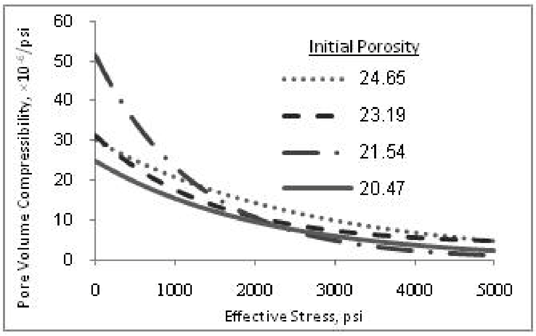

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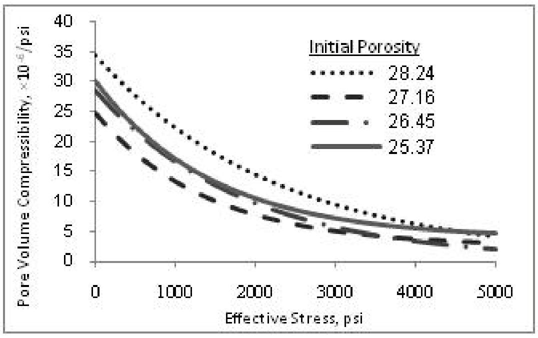

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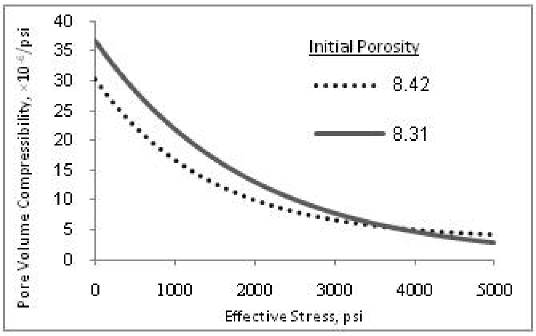

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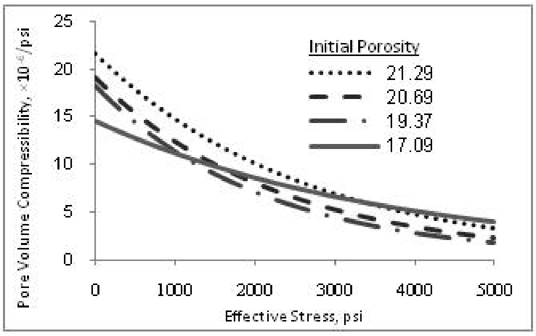
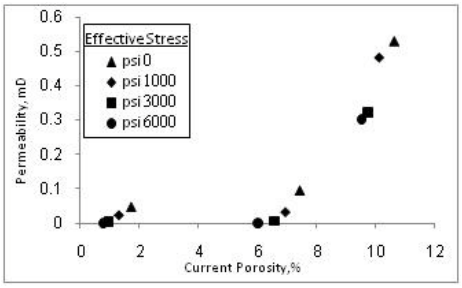


(E)

Figure 4- Relationship between pore volume compressibility and effective stress for different rock types at different initial porosity (A: crystalline limestone, B: separated vuggy pores limestone, C: touching vuggy pores limestone, D: mud-dominated dolomite and E: grain-dominated dolomite.)

Figure 5 shows curves of permeability versus current porosity at different effective stress levels for different rock types. The figure depicts a positive exponential relationship between permeability and porosity. According to the figure it is perceived that changing the stress value leads negligible change in permeability-porosity curve trend. Also, with increasing the stress, the permeability-porosity curve moves down. These changes are dominated for the touching vuggy limestones. Because in the touching vuggy limestone the effective stress increase causes to seal the connecting paths, resulting the permeability decrease but not a significant change in porosity. In mud and grain-dominated dolomite due to compaction, pore size and permeability are reduced as a function of decrease in interparticle porosity. So, in the two dolomites, change in permeability-porosity trend is proportional. It is in agreement with the studies by Cruz (1997) and Lucia *et.al.*, (2001). Although, interpretation of the mud-dominated dolomite behavior is not attributable due to the data shortage in the present study.



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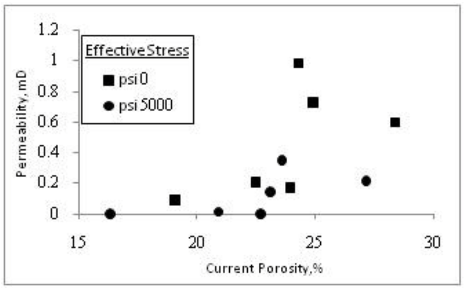

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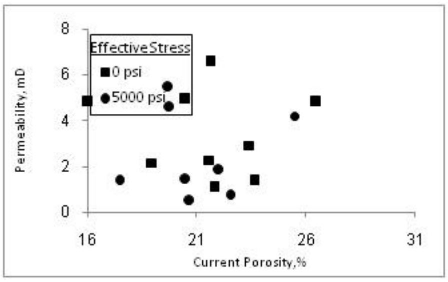

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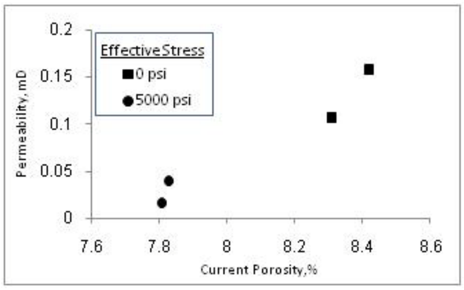

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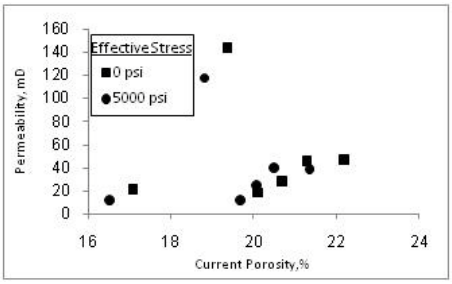


(E)

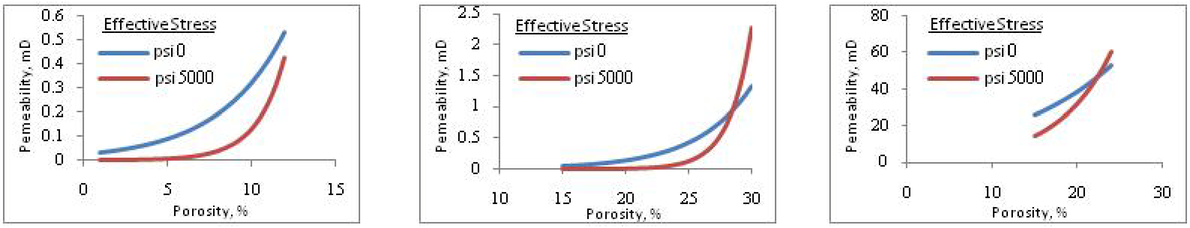
Figure 5: Permeability vs. current porosity at different effective stress levels for different rock types (A: crystalline limestone, B: separated vuggy pores limestone, C: touching vuggy pores limestone, D: mud- dominated dolomite and E: grain-dominated dolomite.)

The interparticle porosity defines the permeability within the separated vuggy limestone because pore size is related to the volume of interparticle pore space as well as grain size and distribution. Hence, changes in interparticle porosity by changing the effective stress will tend to change the pore size distribution and consequently change permeability. Therefore, permeability in separated vuugy limestone is a function of interparticle porosity, grain size and distribution.

Table 2 depicts the exponential correlation between permeability and porosity of the five rock types. As mentioned before, there is a positive exponential relationship between permeability and porosity except in touching vuggy pore system. The irregular scattered data is form the situation of the frequency of connecting paths in the touching vuggy limestone samples. Because the relationship between the frequency of open connecting paths is variable in the samples, permeability and porosity could not correlated in this rock type. These equations may be useful to predict the permeability within the in-situ reservoir conditions. As it can be seen from Figure 6 increasing the effective stress leads to decrease the permeability-porosity curve at low porosity. But at higher porosity values, increasing the effective stress leads to increase the permeability-porosity curve.

Table 2: Relationship between permeability and porosity at two stress levels (A: crystalline limestone, B: separated vuggy pores limestone, C: touching vuggy pores limestone, D: mud- dominated dolomite and E: grain-dominated dolomite.)

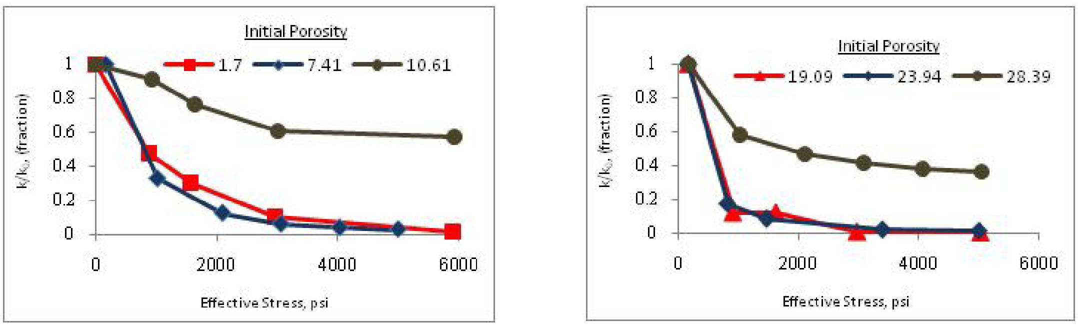
Stress (psi) / Rock Type	0	5000
A	$k = 0.0244 exp(0.2566\varphi)$	$k = 0.00064 exp(0.4419\varphi)$
B	$k = 0.0014 exp(0.2286\varphi)$	$k = 7 \times 10^{-8} exp(0.5766\varphi)$
C	Irregular scattered data.	
D	It is not interpretable due data shortage.	
E	$k = 7.9928 exp(0.0790\varphi)$	$k = 1.3725 exp(0.1576\varphi)$



(A) (B) (E)

Figure 6: Exponential correlation between permeability and porosity (A: crystalline limestone, B: separated vuggy pores limestone, and E: grain-dominated dolomite.)

Figure 7 shows permeability fraction, $\mathbf{k/k_0}$, (where k is current permeability and k_0 is initial permeability) versus effective stress at different initial porosities for different rock types. As it is clear, the permeability decreases smoothly and becomes almost constant above higher stress values. It means that, with increasing effective stress, permeability for all rock types decreases. Furthermore, in all rock types excluding category C, with increasing initial porosity, permeability increases at a same effective stress. In the touching vuggy pores limestone there is not any regular trend to discuss, and it is related to the frequency of connecting paths between pores. Still, due to lack of data in category D, the mud-dominated dolomite, it needs more experiments to obtain a better discussion.



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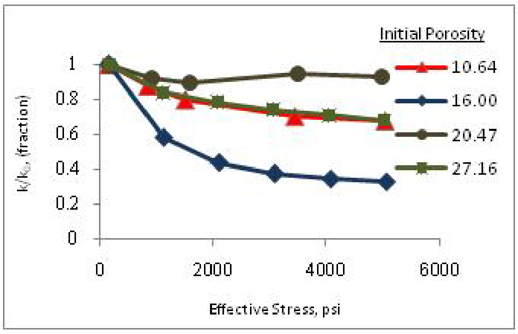

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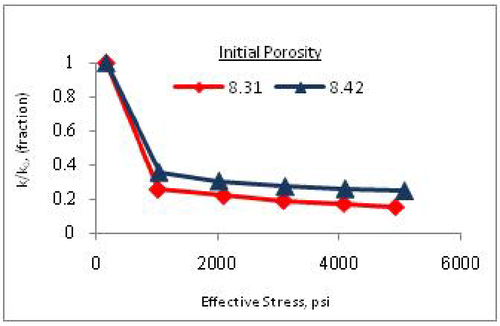

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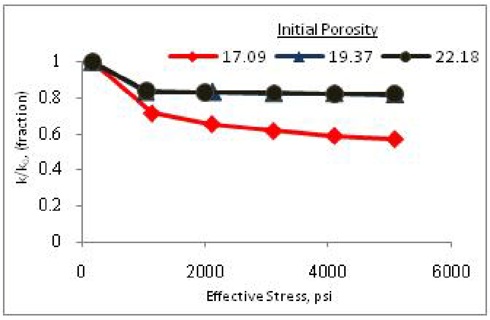

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Figure 7: Permeability fraction (k/k_0) vs. effective stress at different initial porosity for different rock types (A: crystalline limestone, B: separated vuggy pores limestone, C: touching vuggy pores limestone, D: mud- dominated dolomite and E: grain-dominated dolomite.)

Conclusion

The relationship between rock types and pore volume compressibility characteristics, permeability-porosity and permeability-stress relationships is discussed in this research. The porosity measurements were done by Helium injection into the core plugs and also Klinkenberg permeability was determined at some stress levels, simultaneously. As this paper paid for the importance of rock type on these characteristics, initially we grouped the core samples in five categories based on rock types. Later, the results were presented for different rock types, separately.

The proposed relationship in Eq. (1) shows an excellent correlation with experimental data. It is obvious that increasing effective stress decreases pore volume compressibility. We found that, there is a strong negative linear correlation between each pair of initial porosity and coefficient a in the crystalline and separated vuggy pores limestones. It means that, in the crystalline and separated vuggy pores limestones; the initial porosity data have a negative linear relationship with the coefficient a data. But there isn't such a relationship for touching vuggy pores limestones. Although in touching vuggy pores limestones; one couldn't see any linear relationship between the data pairs of the initial porosity and the coefficient a. However some negative correlation could be seen. Also, there was no evidence of any obvious linear correlation between the initial porosity and the other coefficients; C_{pc}^{∞} and b.

There is a positive exponential relationship between permeability and porosity. As in the touching vuggy limestone the effective stress increase causes to seal the connecting paths, the changes in permeability-porosity curve with effective stress was dominant. In the mud and grain-dominated dolomite due to compaction the pore size and permeability are reduced as a function of decrease in interparticle porosity. In the touching vuggy limestone samples, the irregular scattered permeability- porosity data results from the frequency of connecting paths. Increasing the effective stress causes to decrease the permeability-porosity curve at low porosity and in higher values of porosity it tends to increase (Figure 6).

In all rock types, excluding touching vuggy pores limestone, increasing the initial porosity causes to increase the permeability at the same effective stress value. In the touching vuggy pores limestone there wasn't any regular trend to discus, which is related to the frequency of connecting paths between pores. Also, due to lack of data in the mud-dominated dolomites, more experiments are needed to discuss.

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References

Biot, M. A., 1941. General theory of three-dimensional consolidation. Journal of Applied Physics, 12, 155–164.

Biot, M. A., Willis, D.G., 1957. The elastic coefficients of the theory of consolidation. Journal of Applied Mechanics, 24, 594–601.

Cruz W.M., 1997. Study of Albian carbonate analogs: Cedar Park Quarry, Texas, USA, and Santos Basin Reservoir, Southeast Offshore of Brazil. Unpubl PhD thesis, The University of Texas at Austin, Austin, Texas.

Dong, J.-J., J.-Y. Hsu, Wen-Jie Wu, Shimamoto, T., Hung, J.H., Yeh, E.C., Wu, Y.H., Sone, H., 2010. Stress-dependence of the permeability and porosity of sandstone and shale from TCDP Hole-A. Int. J. Rock Mech. Min. Sci. 47(7), 1141-1157.

Fatt, I., 1958. Pore Volume compressibilities of sandstone reservoir rocks. Petroleum Transactions, AIME.

Geertsma, J. 1957. The effect of fluid pressure decline on volumetric changes of porous rocks. Petroleum Transactions, AIME 210, 331-340.

Ghabezloo, S., J. Sulem, Gue´don, S., Franc-ois, M., 2009. Effective stress law for the permeability of a limestone. Int. J. Rock Mech. Min. Sci. 46(2), 297-306.

Hall, H. N., 1953. Compressibility of reservoir rocks. Petroleum Transactions, AlME, 198, 309-311.

Han, G., Dusseault, M. B., 2003. Description of fluid flow around a wellbore with stress-dependent porosity and permeability. J. of Pet. Sci. Eng. 40(1-2), 1-16.

Iscan, A.G., Kök, M.V., Bagc, A.S., 2006. Estimation of permeability and rock mechanical properties of limestone reservoir rocks under stress conditions by strain gauge. J. . Pet. Sci. Eng. 53(1-2), 13-24.

Jalalh, A., 2006. Compressibility of porous rocks: Part I. Measurements of Hungarian reservoir rock sample. Acta Geophysica, 54(3), 319-332.

Kreher, W., Schöpf, H.G., 1973. Effective elastic-plastic compressibility of porous bodies. Int. J. Solids Structures, 9(11), 1331-1348.

Liu, H.-H., Rutqvist, J., Berryman, J.G. 2009. On the relationship between stress and elastic strain for porous and fractured rock. Int. J. Rock Mech. Min. Sci., 46(2), 289-296.

Lucia, F.J., Jennings, J.W., Meyer, F.O., Rahnis, M., 2001. Permeability and rock fabrics from wireline logs, Arab-D reservoir, Ghawar Field, Saudi Arabia. GeoArabia, 6(4), 619–646.

Lucia, F.J. 2007. Carbonate ceservoir characterization, an integrated approach. 2nd Ed., Springer.

Luo, R., Feng, H., 2009. Deformation Characteristics of Low Permeability Rocks under Confining Pressure. Flow in Porous Media-International Forum on Porous Flow and Applications. Wuhan City, CHINA, 21-26.

Medina, C. R., J. A. Rupp, Barnes, D.A., 2011. Effects of reduction in porosity and permeability with depth on storage capacity and injectivity in deep saline aquifers: A case study from the Mount Simon Sandstone aquifer. Int. J. Greenhouse Gas Control, 5(1), 146-156.

Newman, G.H., 1973. Pore-volume compressibility of consolidates, friable, and unconsolidated reservoir rocks under hydrostatic loading. Journal of Petroleum Technology 25(2), 129-134.

Rhett, D.W., Teufel, L.W., 1992. Effect of Reservoir Stress Path on Compressibility and Permeability of Sandstones. SPE 24756, presented at 67th Annual Technical Conference and Exhibition of the Society of

Petroleum Engineering, Washington, DC, October, 4-7.

Terzaghi K., 1936. The shearing resistance of saturated soils and the angle between the planes of shear. In: Proceedings of the first international conference on soil mechanics, vol. 1. Cambridge: Harvard University, 54–56.

Zheng, Z., 1993. Compressibility of porous rocks under different stress conditions. Int.J. Rock Mech. Min. Sci.& Geomech. Abstr. 30(7), 1181-1184.