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Determination of the Vuggy Porosity of Some Oolitic Building Limestones and the Practical Implications

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Abstract

This study shows that a better correlation between different variables such as on sonic velocity, total porosity and water saturation, and other secondary porosity values, can be obtained when dealing with a database, consisting of one petrographic class or Lithological group. This study is based mainly on oolitic limestones of Jurassic age commonly used as building stones in France, Britain and other countries. Few samples have also been taken from Jordan's Holocene. The total porosity is divided into matrix and secondary porosity. Using the cementation exponent (m), only secondary porosity of the moldic or vuggy type was emphasized in the present study. The relationships between the different porosity types and the other measured or derived properties were delineated, by extrapolation, using correlation. Mathematical formulae were presented to derive additional, complex properties from those more easily measured. Although the findings of this study are based on a limited available database about Jordanian building limestone, they have been verified. Practical implications of the present study and its limitations are also discussed.

Keywords: secondary porosity estimation; vug porosity; limestone; oolitic; petrophysics; Jurassic; France; UK; building stone;

1. Introduction

Carbonate rocks (limestone and dolomite) are significant oil and groundwater reservoirs, as well as, building stone resources. Their complicated porosity systems impart heterogeneity to reservoirs (Mazzullo and Chillingarian, 1992) and strongly affect many technical and industrial aspects related to their exploitation. Hence, the specific types and relative percentages of pores present, and their distribution within the rock, exert a strong control on the production and stimulation characteristics of carbonate reservoirs (Jordy, 1992; Chillingarian et al., 1992; Hendrickson et al., 1992; Honarpour et al., 1992; Wardlaw, 1996); salt crystallization (Leary, 1983) and on the restoration and repair of building stones (Ashurst and Dimes, 1990; Spry, 1982).

Limestone porosity can be subdivided according to Choquette and Pray (1970) into the following two types: (1) depositional or primary porosity; such pores could be present between particles or crystals (*inter-particle or inter-crystalline porosity*), or within them (*intra-particle or intra-crystalline porosity*), or formed by gas bubbles and sediment shrinkage (*fenestral porosity*), and as *shelter* or *growth-framework pores* (common in reef buildups); and (2) secondary porosity: which is formed as a result of later, generally post-depositional dissolution or fracturing. Such pore types include those mentioned earlier (when subsequently cemented and later have had all or some of that cement dissolved), as well as vugs (large pores that transect the rock fabric) and dissolution-enlarged fractures.

Primary porosity is substantially reduced by cementation and compaction during post depositional burial diagenesis. Thus, most of the porosity in limestone reservoirs is of secondary origin. However, primary porosity may be preserved because of the early influx of hydrocarbons into pores (e.g. Feazel and Schatzinger, 1985). Also, secondary porosity in carbonate rocks can be formed at, or near the Earth's surface by freshwater dissolution, as well as deep in the subsurface by chemically aggressive (corrosive) fluids. Assigning the pores to one of these two environments (Mazzullo, 2004), requires careful observation, thin-section petrographic study and stable carbon-oxygen isotope analysis.

Oolites are spherical to ellipsoidal bodies, about 0.25 to 2.0 mm in diameter, which may or may not have a nucleus and have concentric or radial structure or both (Glossary of Geology and Related Sciences, 1962). Recent and ancient calcareous ooids and pisoids have been known in the following depositional environments (Flugel, 1982):

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1. Terrestrial (caliche-ooids, cave pearls, pisoids in shallow pools on a playa surface)
2. Fluviatile
3. Lacustrine
4. Marine.

Cavernous and associated vuggy porosity present in oolitic and bioclastic limestones are dominant in some building stones (Honeyborne, 1982; Leary, 1983) and constitute major attributes of hydrocarbon production (Newell et al. 1987; Mazzulo and Chillingarian, 1996; Yousef and Norman, 1997; Fox and Albrandt, 2002).

In developing countries, such as Jordan, where sophisticated laboratory tests are rarely performed due to lack of facilities, there is the need to develop simple estimation techniques by which different porosity types and volumes can be measured. This will be of importance in exploration projects for hydrocarbons, water and minerals currently carried out in Jordan mainly by the National Oil Company, Water Authority and Natural Resources Authority. In this context, (Moh'd, 2002) derived some pore-related properties from bulk density and water saturation, and further work on the secondary porosity of some Jordanian building limestones has been carried out (Moh'd, 2007).

The present work characterizes the vuggy porosity and its volume in French, British and Jordanian building limestones using only Vp (longitudinal sonic waves), total porosity and water saturation. To calculate the cementation exponent (m), there is a need to determine water resistivity (R_w). This value was assumed to be 0.005 ohm-m. It has been reported (Focke and Munn, 1987) that formation's resistivity factors (and consequently cementation exponents) are not affected by the brines resistivity.

2. Materials and Methods

The studied limestones along with their salient petrographic features are summarized in Table 1. Fifty-four samples have been studied in the present work (16 from France, 16*2 from Britain, and 6 from Jordan). As far as the studied UK stones are concerned, each reported reading represents the average of two samples. Studied building stones from France and UK are of Jurassic age and one is of Cretaceous age; all are dominantly ooidal limestones. Jordanian ooidal limestones are of Recent age.

Table 2 characteristics of the studied oolitic building limestones (after Leary, 1983).

The results of porosity, degree of saturation, and sonic velocity (Vp) tests (Brown, 1981), carried out following the BRE testing procedures (Ross and Butlin, 1989), have been taken from Honeyborne (1982) and Leary (1983) for the reported French, and British stones, respectively and measured by the author for the Jordanian oolitic limestones (J1-J6). A set of vuggy non-oolitic Jordanian limestones (J7-J11) (Moh'd, 2007) has been included for comparative purposes. The derived properties include:

Modified saturation: this was obtained by multiplying total porosity with degree of saturation.

Cementation exponent (m): this was calculated using Archie formula and assuming that water resistivity as 0.005 where m= log (0.005/water saturation squared)/log total porosity. This parameter can also be estimated from total and sonic porosity for fractured (Rasmus, 1983) and vuggy carbonates (Nugent, 1983).

Permeability: was obtained using Jorgensen equation (1988) by multiplying 84105 by porosity index = $\Phi^{m+2}/(1-\Phi)^2$. The obtained values were found to correlate well with measured air permeability using API standards.

Table 1 Characteristics of the studied building limestones (after Honeyborne, 1982; Leary, 1983; Moh'd, 2001 and Moh'd, 2007).

Stone Originee	Stone	Description
French Stones	Savonnieres Stone	shelly oolitic limestone, numerous small pockets (6: demi-fine, 7: demi-fine choix, 8: eveillee). Upper Jurassic (Portlandian).
	Brauvilliers Stone	oolitic limestone with occasional shell fragments and some vacuoles (9: liais, 10: liais marbrier, 11: doux demi-fin). Upper Jurassic (Portlandian).
	Anstrude Stone	crinoidal oolitic limestone (14: roche Claire, 15: roche jaune claire, 16: roche jaune). Jurassic (Bathonian).
	Massangis Stone (20)	oolitic limestone with shell fragments (occasional siliceous or pyritized nodules). Jurassic (Bajocian to Bathonian).
	Vilhonneur Stone	oolitic limestone (37: dur, 38: marbrier, 39: roche).
	Sireuil Stone (40)	fine-medium, ooliths, quartz, microfossils, matrix: microgranular, numerous small pockets. Cretaceous (Cenomanian).
	Terce Stone (50)	chalky oolitic limestone. Jurassic (Callovian).
	Chauvigny Stone (53)	oolitic limestone, micritic matrix with macropores. Jurassic (Bathonian).
UK Stones	Ketton Stone	oolitic limestone. Middle Jurassic.
	Portland Stone	oolitic limestone. Late Jurassic.
	Taynton Stone	oolitic limestone from the Great Oolite of Jurassic age.
	Weldon Stone	oolitic limestone. Middle Jurassic.
Jordanian Stones	Oolitic limestones (J1-J6)	from Irkheim Formation, Holocene, hot-water Lake.
	Vuggy non-oolitic limestones	J7-J11
	Hayyan Stone (J7)	fossiliferous limestone, Turonian (Middle Cretaceous).
	Siwaqa Stone (J8 and J9)	Travertine, Holocene.
	Tafih Stone (J10)	Crystalline limestone, slightly phosphatic, Santonian (Upper Cretaceous).
	Izrit Stone (J11)	red chalky limestone, Eocene.

Sonic porosity: is equivalent to velocity of sound – 141/(28.59); where 28.59 is the inverse of 100/(3000-141); 141 and 3000 are transit time (in µ s/m) in calcite crystal and air, respectively.

Vuggy porosity and *Fracture porosity*: are estimated from the dual porosity chart of Aguilera and Aguilera (2003).

Matrix porosity is the total porosity minus the sum of vug and fracture porosities.

3. RESULTS

The results of the present work are listed in Table 2 and shown as bivariate cross-plots in Figures 1 to 20. A simple statistical summary showing the mean, minimum and maximum values of the studied properties are shown in Table 3. A matrix showing the correlation coefficients between the different variables is shown in Table 4. These are usually the minimum values of correlation coefficients because in these softwares (such as Excel which was used to obtain the correlation matrix here) linear relationships are assumed between the variables. As shown in the Figures, higher values of correlation coefficients can be obtained when fitting the data using nonlinear models.

Table 2 Measured ([1, 2, 3] after Honeyborne, 1982) and derived properties of the studied stones.

Stone	Subtype	Bed	Sound Velocity1 m/s	Total Porosity2 %	Water Saturation3	modified saturation	Cementation Exponent	Permeability millidarcies	Sonic porosity %	Secondary Porosity %	Vuggy Porosity %	Matrix Porosity %
Ketton		Old	3450	23.8	0.65	15.44	3.09	96	5.2	18.5	13.5	10.3
		New	2750	23.7	0.65	15.41	3.08	96	7.8	15.9	13.5	10.2
		White	2900	24.8	0.65	16.12	3.18	109	7.1	17.7	14.0	10.8
Portland	Independ.	Whit	3850	13.6	0.92	12.47	2.57	12	4.2	9.4	6.3	7.3
		Base	3950	13.0	0.96	12.43	2.55	10	3.9	9.0	5.3	7.7
	Kingston	Roach	3925	19.6	0.59	11.58	2.61	72	4.0	15.7	9.5	10.1
		Whit	3775	22.2	0.62	13.75	2.88	89	4.3	17.9	13.5	8.7
		Base	3875	19.1	0.70	13.36	2.77	58	4.1	15.0	11.0	8.1
	Sheat Q.	Top Tier	3900	20.2	0.60	12.09	2.67	74	4.0	16.1	9.9	10.3
		Mid Tier	3550	20.6	0.59	12.12	2.68	81	4.9	15.6	10.0	10.6
		SeedyTier	3700	17.6	0.68	11.97	2.61	41	4.5	13.1	8.0	9.6
		Base	4100	16.5	0.67	11.06	2.50	36	3.6	12.9	7.5	9.0
		Roach	3300	21.0	0.64	13.44	2.82	73	5.7	15.3	12.4	8.6
Taynton			3550	23.5	0.69	16.22	3.15	83	4.9	18.6	14.0	9.5
Weldon		Fine G.	2600	27.1	0.68	18.43	3.47	125	8.5	18.6	15.5	11.7
		Coarse G.	1900	27.2	0.66	17.92	3.43	133	13.5	13.7	15.5	11.7
		6	2881	36.1	0.52	18.77	3.92	495	7.2	28.9	22.5	13.6
		7	2684	34.7	0.50	17.35	3.70	473	8.1	26.6	22.0	12.7
		8	2702	30.6	0.68	20.81	3.82	177	8.0	22.6	18.0	12.6
		9	3106	27.0	0.57	15.39	3.19	177	6.3	20.7	17.0	10.0
		10	2966	32.6	0.54	17.60	3.63	336	6.9	25.7	19.0	13.6
		11	3045	33.7	0.47	15.84	3.48	493	6.6	27.2	20.0	13.7
		14	3376	21.9	0.81	17.74	3.21	31	5.4	16.5	13.0	8.9
		15	3374	20.6	0.66	13.60	2.83	65	5.4	15.2	10.0	10.6
		16	4282	18.1	0.65	11.77	2.60	48	3.2	14.9	8.5	9.6
		20	4276	15.1	0.88	13.29	2.67	17	3.3	11.9	10.0	5.1
		37	4684	13.1	0.89	11.66	2.49	12	2.5	10.6	5.0	8.1
		38	4259	11.7	0.94	11.00	2.41	8	3.3	8.4	4.1	7.6
		39	4606	11.9	0.64	7.62	2.07	19	2.7	9.3	1.3	10.7
		40	2069	36.0	0.76	27.36	4.65	230	12.0	24.0	22.5	13.5
		50	3332	23.7	0.88	20.86	3.50	53	5.6	18.1	14.0	9.7
		53	4014	18.7	0.71	13.28	2.75	44	3.8	14.9	5.3	13.4
		J1	4005	15.1	0.65	9.82	2.35	31	3.8	11.3	5.0	10.1
		J2	3991	16.7	0.69	11.52	2.55	35	3.8	12.9	6.0	10.7
		J3	4090	15.2	0.68	10.34	2.40	29	3.6	11.6	5.4	9.8
		J4	3899	17.1	0.66	11.29	2.53	41	4.0	13.1	7.0	10.1
		J5	3945	14.3	0.69	9.87	2.34	25	3.9	10.4	4.8	9.5
		J6	4020	15.4	0.73	11.24	2.50	26	3.8	11.6	7.2	8.2
		J7	4704	14.8	0.77	11.37	2.50	21	2.5	12.3	5.5	9.3
		J8	3792	17.9	0.76	13.59	2.76	35	4.3	13.6	9.9	8.0
		J9	4085	17.8	0.79	14.05	2.79	32	3.6	14.2	10.0	7.8
		J10	4012	22.9	0.56	12.81	2.81	118	3.8	19.1	12.5	10.4
		J11	3849	19.9	0.85	16.94	3.08	36	4.2	15.8	11.2	8.7

Table 3 Mean, minimum and maximum of the studied properties.

	Mean	Minimum	Maximum
Sonic Velocity	3544.24	1900.00	4684.00
Total Porosity	21.38	11.70	36.10
Water Saturation	0.69	0.47	0.96
Modified Saturation	14.26	7.62	27.36
Cementation Exponent	2.94	2.07	4.65
Permeability	106.71	8.39	494.61
Sonic Porosity	5.35	2.54	13.48
Secondary Porosity	16.03	8.42	28.89
Vuggy Porosity	11.23	1.25	22.50
Matrix Porosity	10.15	5.10	13.70

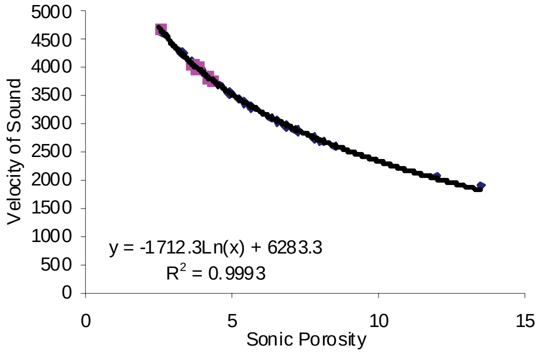

Figure 1 Deriving sonic porosity from velocity of sound.

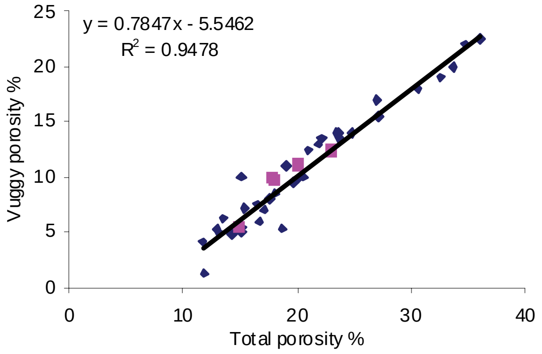

Figure 2 Deriving vuggy porosity from total porosity.

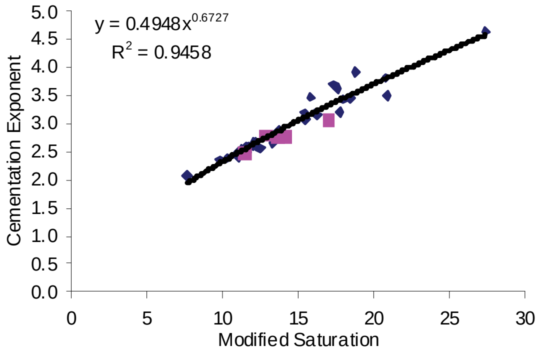

Figure 3 Deriving cementation exponent from modified saturation.

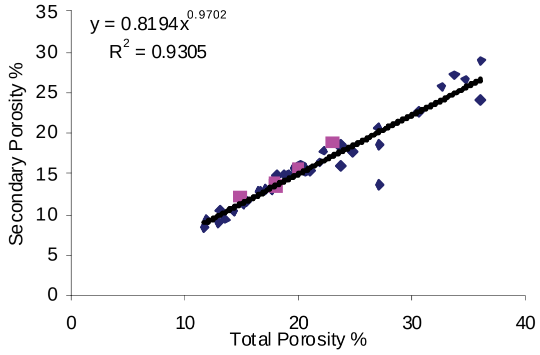

Figure 4 Deriving secondary porosity from total porosity.

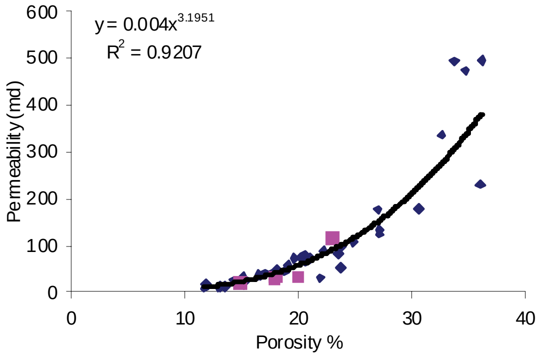

Figure 5 Deriving permeability from porosity.

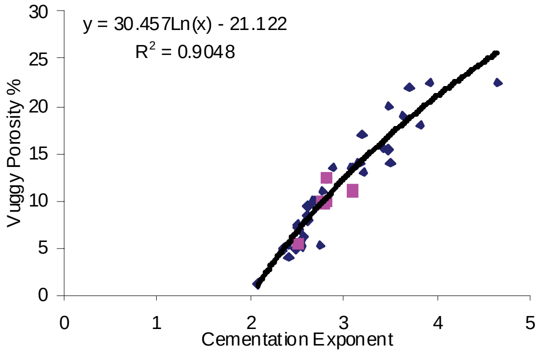

Figure 6 Deriving vuggy porosity from cementation exponent.

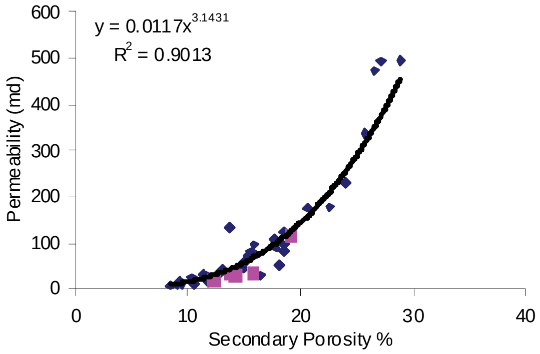

Figure 7 Deriving permeability from secondary porosity.

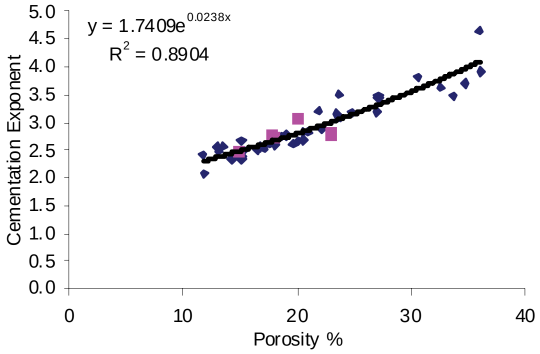

Figure 8 Deriving cementation exponent from total porosity.

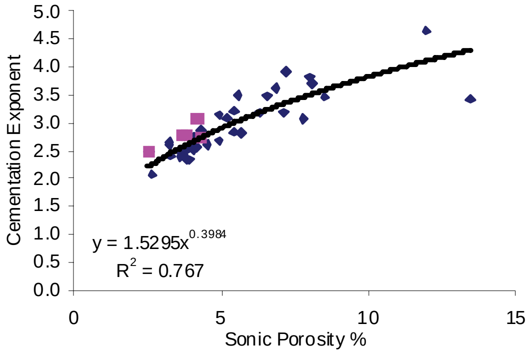

Figure 12 Deriving cementation exponents from sonic porosity.

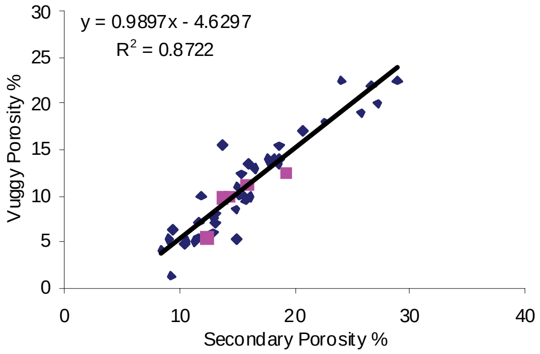

Figure 9 Deriving vuggy porosity from secondary porosity.

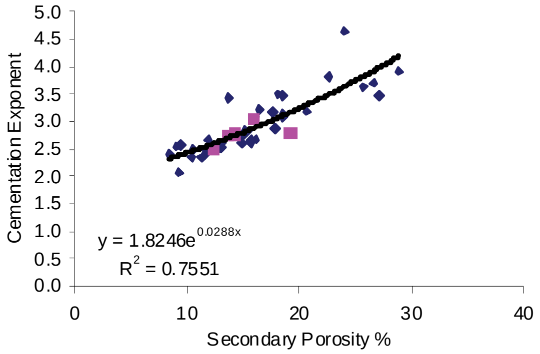

Figure 13 Deriving cementation exponents from secondary porosity.

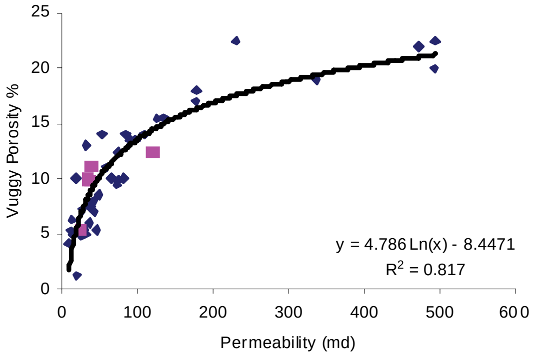

Figure 10 Deriving vuggy porosity from permeability.

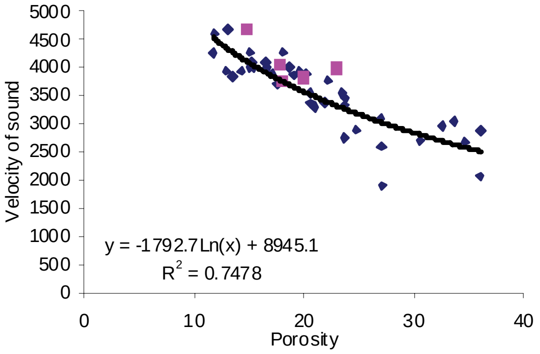

Figure 14 Deriving velocity of sound from total porosity.

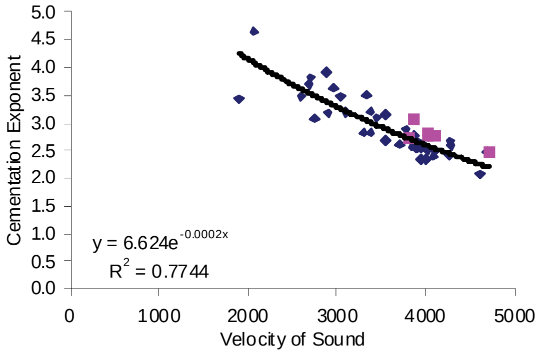

Figure 11 Deriving cementation exponents from velocity of sound.

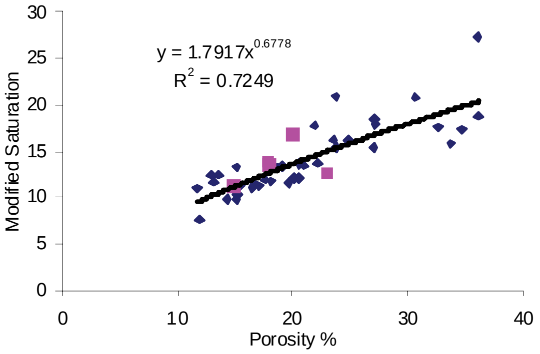

Figure 15 Deriving modified saturation from total porosity.

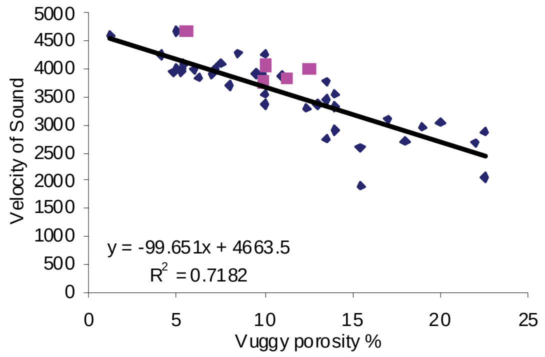

Figure 16 Deriving vuggy porosity from velocity of sound.

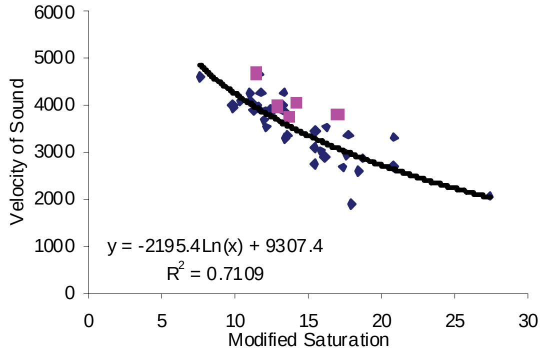

Figure 17 Deriving velocity of sound from modified saturation.

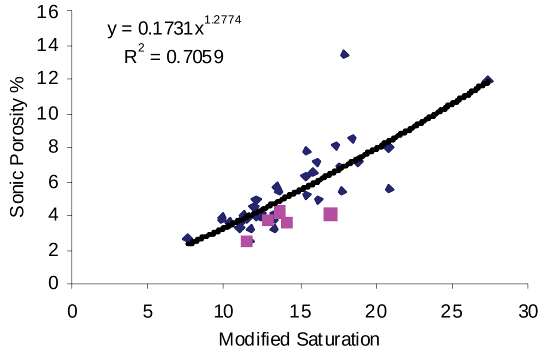

Figure 18 Deriving sonic velocity from modified saturation.

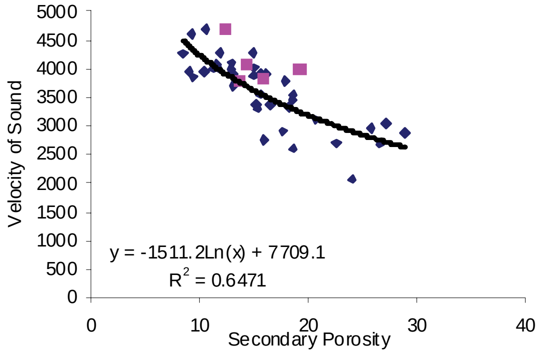

Figure 19 Deriving velocity of sound from secondary porosity.

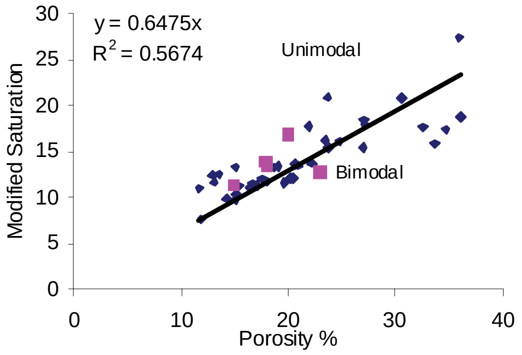

Figure 20 Inferring uni-modality and bi-modality of pores from porosity and modified saturation.

4. Practical Implications

In the case of clean vuggy oolitic limestone, and when it is difficult to have access to sophisticated equipment, the easiest parameter to measure is bulk density, which can be inverted to total porosity (Moh'd, 2002). This method is used to derive secondary porosity (Figure 4), vuggy porosity (Figure 2), permeability (Figure 5), cementation exponent m (Figure 8), and velocity of sound (Figure 14).

Table 4 Correlation matrix between the different measured and derived properties.

	Sound Velocity	Total Porosity	Water Saturation	Modified Saturation	Cement. Exponent	Permeability	Sonic Porosity	Secondary Porosity	Vuggy Porosity	Matrix Porosity
Sound Velocity	1.00									
Total Porosity	-0.86	1.00								
Water Saturation	0.36	-0.57	1.00							
Modified saturation	-0.83	0.83	-0.07	1.00						
Cementation Exponent	-0.87	0.94	-0.27	0.97	1.00					
Permeability	-0.61	0.87	-0.63	0.54	0.72	1.00				
Sonic Porosity	-0.97	0.79	-0.28	0.81	0.83	0.54	1.00			
Secondary Porosity	-0.69	0.96	-0.62	0.73	0.86	0.90	0.58	1.00		
Vuggy Porosity	-0.85	0.97	-0.47	0.85	0.94	0.82	0.77	0.93	1.00	
Matrix Porosity	-0.62	0.76	-0.65	0.51	0.64	0.72	0.59	0.73	0.59	1.00

Modified saturation is estimated from either porosity (Figure 15) or velocity of sound (Figure 17). From the sonic velocity, the sonic porosity is estimated (Figure 1). Subtracting sonic porosity from total porosity gives secondary porosity. Cementation exponent and other porosity types are estimated from sound velocity. The important relations between other parameters were shown in the Figures, which are arranged in descending order according to the value of correlation coefficient (r).

5. Discussions

In Table 3, there are wide ranges in the different properties of the examined oolitic limestones. Vuggy porosity ranges from almost 1% to 25% compared with a total porosity ranging from 11.7% to 36.1%. Sonic velocity is also widely variable ranging from 1900 m/s to 4684 m/s. The almost perfect negative correlation between velocity of sound and sonic porosity (Figure 1) is the outcome of the derivation of the latter from the former. Most of the relationships between the different variables except those involving permeability are linear or semilinear. Cross-plots involving permeability show high curve-linearity (Figures 5, 7, 10). These figures reveal that permeability is a function of porosity (total porosity, secondary porosity and the vuggy porosity). Permeability is defined as the easiness with which fluids move through materials and it is mainly controlled by pore and throat size distribution, and tortuousity of the pore space. Permeability should be correlated with effective porosity (connected pores and fractures) than total porosity as the latter may have isolated or blocked pores.

Vuggy porosity is strongly correlated with total porosity (r = 0.97, Figure 2), cementation exponent (r= -0.95, Figure 6), and secondary porosity (r = 0.93, Figure 9). The higher the cementation exponent is, the higher the vuggy porosity becomes. Similarly, as vuggy porosity is the only secondary porosity type present, it increases as the secondary porosity increases. As far as the relationship with total porosity is concerned, it may be easier for solutions to enlarge the already existing pore space than to create a new one. These variables are derived using the following equations:

$$\text{Vuggy Porosity} = 0.7847 * \text{Total Porosity} + 5.5462$$

$$\text{Vuggy Porosity} = 30.457 \ \text{Ln Cementation Exponent} - 21.122$$

$$\text{Vuggy Porosity} = 0.9897 * \text{Secondary Porosity} - 4.6297$$

Cementation exponent is controlled by the total porosity (r = 0.94, Figure 8) and the modified saturation, which shows the volume of water that can fill the connected pore space (r = 0.97, Figure 3). The following equations reveal these relationships as follows:

$$\text{Cementation Exponent} = 1.7409 \ e^{0.0238 * \text{Total Porosity}}$$

$$\text{Cementation Exponent} = 0.4948 * \text{Modified Saturation}^{0.6727}$$

The permeability of some vuggy and fractured Jordanian limestones was measured (Moh'd, 1996) and found to correlate well with those derived using Jorgensen's equation (Moh'd, 2007). This indicates that this equation, used in this study to estimate permeability, yields reasonable results. By utilizing the relationships between total porosity and cementation exponent, some researchers (e.g. Focke and Munn, 1987) classified vuggy carbonates into different permeability groups (<0.1, 0.1-1, 1-100, >100 millidarcies) based on studying hundreds of vuggy carbonate samples from the oil reservoirs of the Persian Gulf. The permeability of the examined oolitic limestones lies in groups three and four (1-100, >100 millidarcies) of Focke and Munn Classification. The advantage of Jorgensen method over that of Focke and Munn's method is that the former gives exact permeability figures, whereas the latter gives the permeability group.

Taken into account that oolitic limestones are encountered in the surface and subsurface of Jordan in the Cambrian, Jurassic, Cretaceous and Pleistocene (Moh'd and Muneizel, 1998; Powell, 1988; Moh'd, 1993; Moh'd, 2001), the finding of the current study is of interest and application to Jordanian geologists. It is hoped that this study will contribute to a better understanding of the petrophysics of oolitic facies and their subsequent exploitation as hydrocarbon reservoirs, building and industrial materials, as well as water aquifers. However, the findings of the current study are not applicable to oolitic facies if they lack any evidence of dissolution during their post-depositional history such as vugs or larger scale features. Field investigations, petrography or petrophysics can be employed to gather such evidence. When the cementation exponent (*m*) value is much higher than two, it indicates the existence of secondary porosity in the form of moldic or vuggy porosity. Lucia (1983) considered that the higher the value of *m* above two, the higher the ratio of separate vug porosity to total porosity. An approximation of the uni- or bi-modality of pore-size distribution can be easily determined from plotting modified saturation against total porosity (see Figure 20). Modified Saturation used in the present study is the same as bulk water volume used in petroleum engineering literature (Asquith, 1985). It is worth mentioning that the relationships established in the present work are applicable to vuggy or moldic oolitic limestones (with very little dolomite, quartz or clay) only and are not generalized to other carbonate lithologies without conducting further experimental work. In addition, the database (representing 54 ooidal limestone types and subtypes; each UK sample is the average of two samples) is small and larger data bases are needed to check the validity of conclusions in a larger context. Due to the lack of laboratory facilities to measure cementation exponent *m* and permeability, the study relied on published literature to estimate these parameters. Although it is desirable to make a comparison between measured and estimated values of these two properties, it is believed that such differences are small. The present study is designed to address the problem of estimating petrophysical properties of vuggy oolitic limestones when access to sophisticated laboratory equipment is not possible, as the case in Jordan and other developing countries. This study is significant because it identifies the parameters that correlate strongly with other difficult to measure parameters.

6. Conclusions

Despite the limited size of the present database, the study shows that some easily measured parameters can be used in deriving other parameters with strong correlation coefficients, mostly over 0.9. Thus, bulk density can be inverted to porosity, which is in turn can be used to derive many parameters such as permeability and *Vp*. The latter parameter is used in deriving cementation exponent (*m*) and other porosity types. The results are summarized in Table 3. However, it is suggested to utilize a larger database to check the validity of relationships deduced by the present study and to restrict its use to clean vuggy oolitic limestone. It is also suggested to carry out further research to quantify the differences between estimated values of different parameters to laboratory-measured values of these same parameters.

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