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Characterization of the Secondary Porosity of Some Cretaceous-Recent Jordanian Building Limestones

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Abstract: Different types of limestone (including chalk, travertine, marble, wacke stone and packstone-grainstone) commonly used as building stones in Jordan with porosity ranging from around 1% to less than 30% have been covered in this study. The total porosity has been split into matrix and secondary porosity. Types (fracture/moldic) and amounts of secondary porosity have also been defined. The relationships of the different porosity types with the other measured or derived properties have been delineated using correlation. Mathematical formulae have been presented to derive complicated or difficult to measure properties from easily measured ones. As indicated by the calculated cementation exponent value m and documented petrographically, tight limestones are dominated by fracture porosity, whereas highly porous limestones are dominated by moldic porosity. This is well exemplified by Siwaqa travertine where vugs are dominant in the high porosity varieties and fractures in the low porosity samples. Practical implications of the present work and its limitations have also been discussed.

Key words: Dual porosity, building limestone, petrophysics, Jordan

INTRODUCTION

Sound propagation and porosity of limestone have many economic applications in the exploration and exploitation of mineralized ores (and their mining), construction materials and oil and water (Anderson and Nevenst, 1952; Wantland, 1953; Mamillan, 1954; Sutherland, 1962; Belikov, 1967; Duncan, 1969; Griffiths and King, 1969; Atkinson, 1970; Fourmaitraux, 1976; Bell, 1980; Goodman, 1980; Christensen, 1982; Leary, 1983; North, 1985; Odent, 1993; Gueguen, 1994; Moh'd, 1996).

The term total porosity was used in this work to indicate the porosity measured in the laboratory using a vacuum pump (without pulverizing the sample) and to differentiate it from other types of porosity mentioned in the text, although it is known that the only true total porosity is that obtained by pulverizing the sample (Brown, 1981).

Porosity is defined as the percentage of voids in a rock to its total volume (including solid and voids). Unfortunately, in many practical applications including fluid flow in rock, as well as, many technical and industrial problems total porosity alone is not sufficient to give complete and satisfactory answers for many questions. Consequently, there is a need to know the type of porosity present along with its amount.

Carbonates as nearly as all other sedimentary rocks, have high values of porosity at the time of their formation referred to as primary porosity where the pores usually occur between their particles or crystals. With progress of time, the passage of solutions through the rock occasionally may diminish its porosity to less than 5%, as is the case in marbles and tight limestones. Tectonic and dissolution diagenetic processes may lead to fracture and vug porosities. This type of porosity, which forms long after the rock’s deposition, is referred to as secondary porosity. For further details on the classification of limestone porosity refer to Choquette and Pray (1970).

Microcracks can be introduced into, or removed from, a rock by a variety of processes. Some processes such as pressure relief from erosion, meteorite shock impact and cementation from circulating water have a geological cause. Other processes could be due to drilling, hammering or blasting. Despite its importance, there is, so far, little convincing and easy to carry out quantitative work on microcrack characterization (Edet, 1992). However, the research of Aguilera and Aguilera (2003) used seems to be a breakthrough in this field. Using total porosity and cementation exponent, it can quantify the fracture and moldic porosities. The dual porosity concept, a simple version of Aguilera and Aguilera (2003) in comparison with the triple porosity model was used in the present study.

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 schemes by which different porosity types and quantities are defined. This will be of importance for exploration projects for oil, water and minerals currently carried out in Jordan mainly by the

National Oil Company, Water Authority and Natural Resources Authority. In this context, the present author (Moh'd, 2002) has previously published a paper on deriving some pore-related properties from water absorption and water saturation.

The present research aims at characterizing the secondary porosity of the studied limestones into fracture and moldic (vuggy) types along with their amounts using only Vp, total porosity and water saturation. Of course, for calculating the cementation exponent m, there is a need to know water resistivity (Rw). This value was assumed to be 0.005 ohm m.

MATERIALS AND METHODS

The geology of Jordanian building stones is summarized in Table 1 and the petrography of those selected for the present study is shown in Table 2 (Moh'd, 2002). The petrographic nomenclature is following one or more of the following: Folk (1959, 1962), Dunham (1962) and Fookes and Higginbottom (1975).

The porosity, degree of saturation and sound velocity (Vp) tests were carried out at BRE (UK) and NRA (Jordan) following the BRE testing procedures (Ross and Butlin, 1989).

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 (1988) equation 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.

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.

Vug 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.

Dry density: Is calculated using the following equation
Dry density = grain density (1-fractional porosity)

RESULTS

Test results of measured and derived properties are summarized in Table 3. The studied stones are arranged in ascending order based on the value of their cementation exponent m. The lower part of Table 3 is a correlation matrix for the different studied properties.

Table 1: Stratigraphy of Cretaceous to early Tertiary in Jordan

Tests	Stage	Formation	Symbol	Main lithologies
	Eocene	Shallala/Ma'an*	SH/NML	Chalk; nummulitic limestone
Tertiary		Umm Rijam*	URC	Chalk, chert, limestone
	Paleocene	Muwaqqar*	MCM	Chalk, marl, limestone concretions
Upper	Maestrichtian	Al Hisa	AHP	Phosphorite, limestone, chert
Cretaceous	Santonian/Camp.	Amman	ASL	Chert, limestone, dolomite
		Umm Ghudran	WG	Chalk, Tripoli, chert
Middle	Turonian	Wadi As Sir*	WSL	Limestone, dolomite
	Cenomanian	Shuayb	S	Marl, nodular limestone
Cretaceous		Hummar	H	Dolomite, limestone
		Fuhays	F	Marl, clayey
		Naur*	NL	Limestone, nodular, dolomite
Early Cret.	Albian	Kurnub	KS	Sandstone; occasionally silty clay

*Units with good potential as sources of building stones

Table 2: Petrographic classification of the stones studied

Stone	Unit	Folk (1959; 1962)	Dunham (1962)	Fookes and Higginbottom (1975)
Siwaqa travertine	Recent	Sparite	?	Crystalline limestone
Sat'h, Jazeira	Ma'an	Biosparite	Nummulitic grainstone	Bioclastic limestone
Izrit	Umm Rijam	Biomicrite	Globigerinoid wackestone	Carbonate siltstone (chalk)
Sahrawi red		microsparite	Mudstone	Fine-grained limestone
Tafih	Amman	Sparite?	?	Crystalline limestone
Ajlun, Ballas		Biomicrite	Wackestone	Fine-grained limestone
Hallabat marble	Wadi As Sir	Biosparrudite	Fossiliferous packstone	Bioclastic limestone
Hayyan		Biomicrite	Fossiliferous wackestone	Bioclastic limestone
Yanabi		Pelmicrite	Peloidal packestone	Fine-grained limestone
Karak	Naur	Biosparite	Fossiliferous packstone	Bioclastic limestone

? Classes not known in Folk or Dunham's classifications

Table 3: Measured and derived properties of the studied stones listed and correlated

Stone	Vp m/s	Total porosity (%)	Saturation coefficient	Modified saturation	M	Permeability Md	Sonic porosity (%)	Secondary porosity (%)	Vug porosity (%)	Fatcure porosity (%)	Matrix porosity (%)
Sat'h	5842.00	3.321	0.45	1.494	1.09	2.45	1.055	2.266	0.0	2.2	1.121
Ballas	6050.00	1.476	0.77	1.137	1.13	0.159	0.85	0.626	0.0	0.9	0.576
Jazeira	5712.00	4.428	0.42	1.86	1.14	5.117	1.192	3.236	0.0	3.0	1.428
Yanabi	6330.00	1.476	0.81	1.196	1.16	0.144	0.594	0.882	0.0	0.6	0.876
Karak	5840.00	1.845	0.73	1.347	1.17	0.279	1.057	0.788	0.0	0.8	1.045
Ajlun	5393.00	1.845	0.80	1.476	1.22	0.232	1.55	0.295	0.0	0.8	1.045
Siwaqa trav.	4320.00	5.13	0.45	2.309	1.25	6.072	3.165	1.965	0.0	2.4	2.73
Siwaqa trav.	4235.00	7.29	0.51	3.718	1.51	9.997	3.327	3.963	0.0	1.6	5.69
Sahrawi	5572.00	7.011	0.56	3.926	1.56	7.623	1.346	5.665	0.0	1.5	5.511
Hallabat marble	5734.00	6.273	0.64	4.015	1.59	4.599	1.168	5.105	0.0	1.0	5.273
Siwaqa trav.	5193.00	6.33	0.64	4.051	1.60	4.689	1.804	4.526	0.0	1.0	5.33
Hayyan	4704.00	14.76	0.77	11.37	2.50	21.27	2.504	12.26	5.5	0.0	9.26
Siwaqa trav.	3792.00	17.88	0.76	13.59	2.76	34.52	4.292	13.59	9.9	0.0	7.98
Siwaqa trav.	4085.00	17.78	0.79	14.05	2.79	31.51	3.631	14.15	10.0	0.0	7.78
Tafih	4012.00	22.88	0.56	12.81	2.81	118.00	3.786	19.09	12.5	0.0	10.38
Izrit	3849.00	19.93	0.85	16.94	3.08	36.04	4.156	15.77	11.2	0.0	8.73
Vp	1.00										
Total porosity	-0.84	1.00									
Saturation coeff.	-0.07	0.22	1.00								
Modified saturation	-0.81	0.97	0.40	1.00							
M	-0.81	0.98	0.40	1.00	1.00						
Permeability	-0.62	0.83	0.01	0.69	0.73	1.00					
Sonic porosity	-0.99	0.86	0.11	0.83	0.83	0.64	1.00				
Secondary porosity	-0.78	0.99	0.24	0.96	0.97	0.84	0.79	1.00			
Vug porosity	-0.78	0.96	0.36	0.96	0.96	0.82	0.81	0.96	1.00		
Fracture porosity	0.40	-0.63	-0.83	-0.70	-0.74	-0.49	-0.44	-0.65	-0.70	1.00	
Matrix porosity	-0.80	0.94	0.18	0.89	0.92	0.73	0.79	0.93	0.81	-0.61	1.00

Table 4: A list of significant relationships seen in the correlation matrix and illustrated in Fig 1 to 17

Fig.	Equation	R^2	R
1	Sonic porosity % = $2*10^{13}/\{(Vp)^{3.1543}\}$	0.973	0.986
2	Vug porosity % = -0.0066Vp + 36.996	0.747	0.864
3	Total porosity % = $631.28/e^{0.0009Vp}$	0.724	0.851
4	$5*10^{17}/(Vp)^{4.6227}$	0.703	0.838
5	Cementation exponent M = - 0.0007Vp+5.1926	0.657	0.810
6	Matrix porosity % = $283.49/(e^{0.0009\,Vp})$	0.614	0.784
7	Secondary porosity % = 0.7865*total porosity	0.980	0.990
8	Cementation exponent M = 0.098*total porosity+0.9171	0.955	0.977
9	Modified saturation = 0.7066*total porosity	0.939	0.969
10	Matrix porosity % = 0.4888*total porosity	0.823	0.907
11	Vug porosity % = 0.8247*total porosity - 5.5568	0.881	0.939
12	Sonic porosity % = 1.149 Ln total porosity+0.1649	0.708	0.842
13	Fracture porosity % = $0.4359/(\text{degree of saturation})^{2.0836}$	0.957	0.978
14	Cementation exponent M = 0.1301*modified saturation+0.998	0.991	0.995
15	Secondary porosity % = 1.0823* modified saturation	0.925	0.962
16	Matrix porosity % = 3.3803 Ln modified saturation+0.1542	0.942	0.971
17	Secondary porosity % = 8.2739 * cementation exponent-8.1548	0.947	0.973

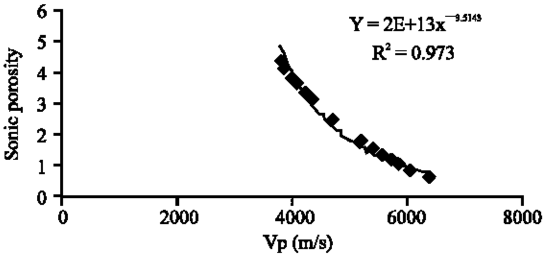

Fig. 1: Deriving sonic porosity from Vp

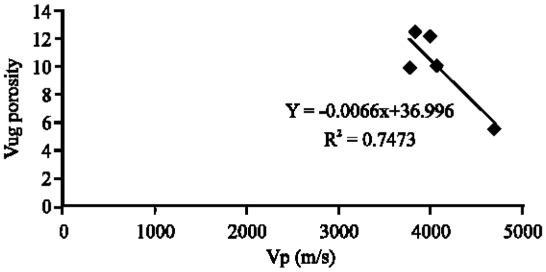

Fig. 2: Deriving vug porosity from Vp

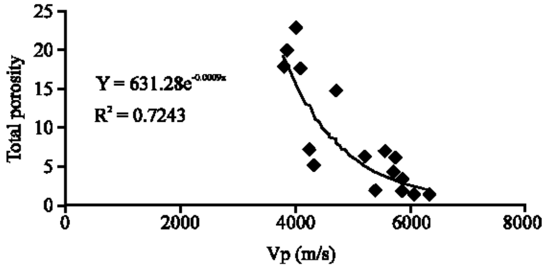

Fig. 3: Vp versus total porosity

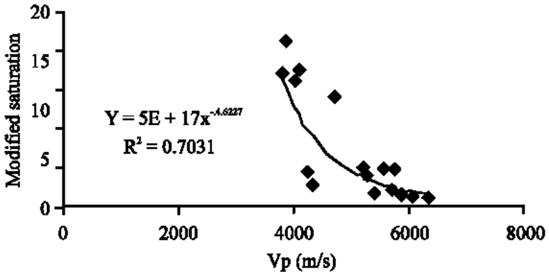

Fig. 4: Vp versus modified saturation

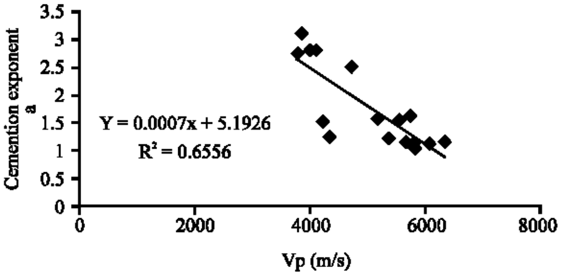

Fig. 5: Vp versus cementation exponent (m)

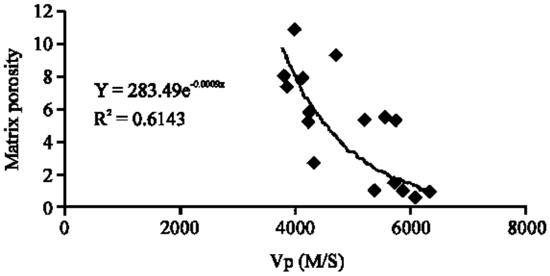

Fig. 6: Vp versus matrix porosity

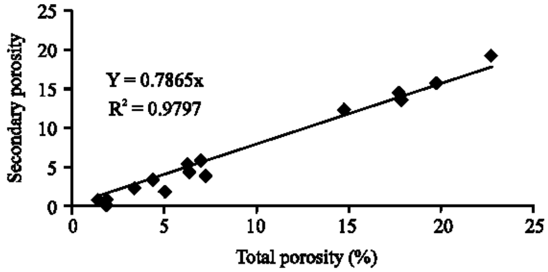

Fig. 7: Deriving secondary porosity from total porosity

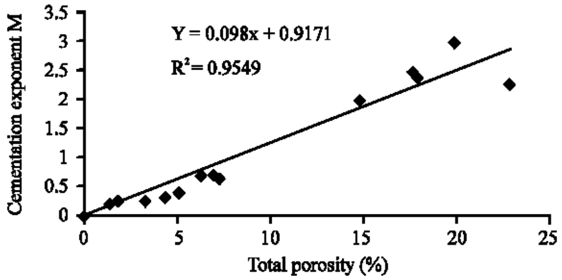

Fig. 8: Deriving secondary porosity from total porosity

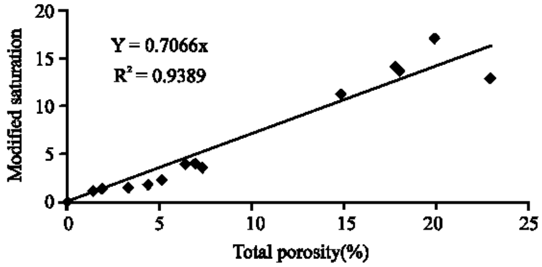

Fig. 9: Deriving modified saturation from total porosity. Area below best-fit line represents bimodal and polymodal pores

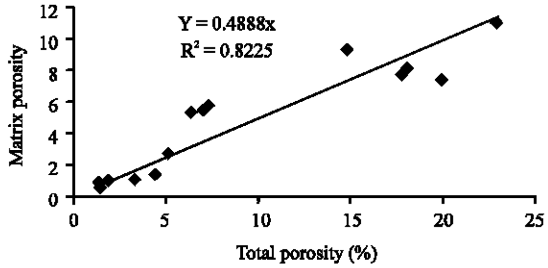

Fig. 10: Deriving matrix porosity from total porosity

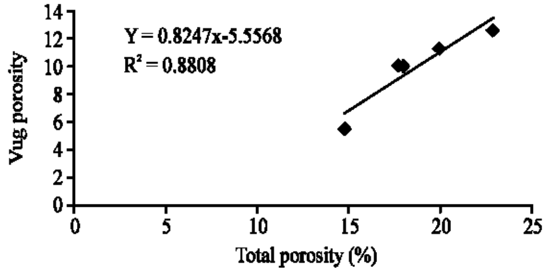

Fig. 11: Deriving vug porosity from total porosity

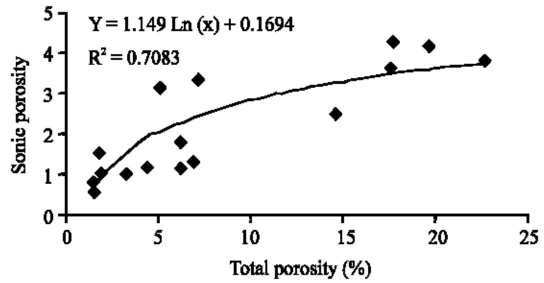

Fig. 12: Deriving sonic porosity from total porosity

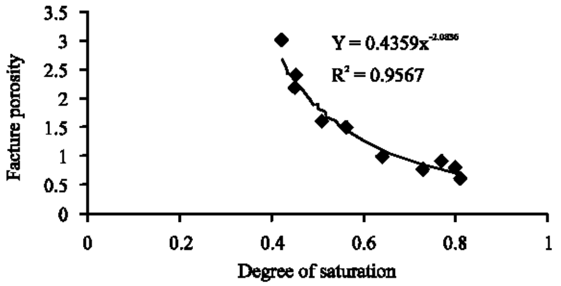

Fig. 13: Deriving fracture porosity from degree of saturation

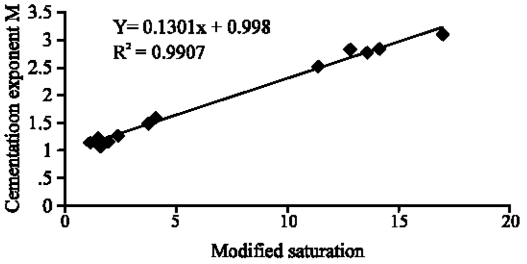

Fig. 14: Deriving cementation exponent M from modified saturation

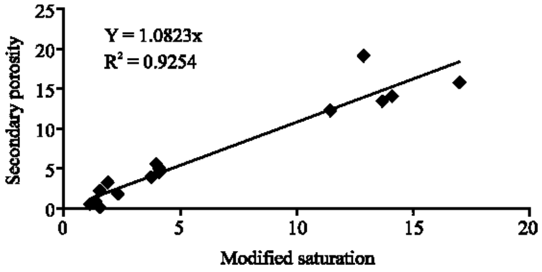

Fig. 15: Deriving secondary porosity from modified saturation

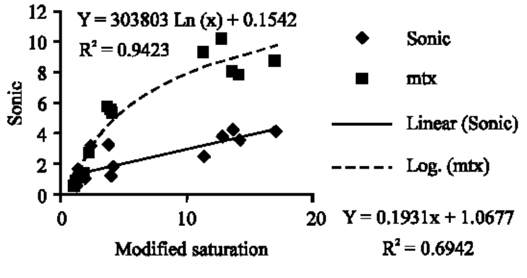

Fig. 16: Deriving sonic and matrix porosity from modified saturation

Significant correlations between different parameters as seen in the correlation matrix assume linear best-fit lines

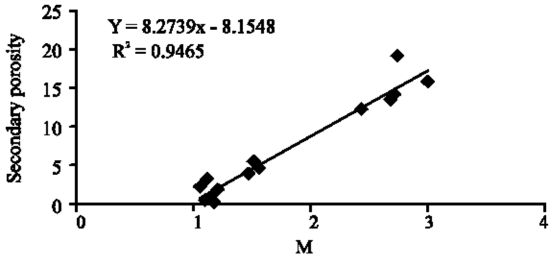

Fig. 17: Deriving secondary porosity from cementation exponent M

(better in case of non-linear relationships) are plotted in Fig. 1 to 17 and summarised in Table 4.

DISCUSSION

When there is no secondary porosity, values of cementation exponent (m) will be equal to or around 2 indicating inter-particle or inter-crystalline porosity. Consequently, the total porosity will be wholly of the matrix type. When m values are less than 2 then part of the total porosity will be secondary and of fracture type, whereas, m values much higher than 2 reflect the existence of secondary porosity in the form of moldic or vuggy porosity. Lucia (1983) considered that the higher the value of m above 2, the higher the ratio of separate vug porosity to total porosity. An idea about the uni- or bi-modality of pore-size distribution can be easily gained from plotting modified saturation against total porosity (Fig. 9). Modified saturation used in the present work is the same as bulk water used in petroleum engineering literature. It is important here to mention that the relationships achieved to in the present work are restricted to clean limestones (with very little dolomite, quartz or clay) and should not be generalized to other lithologies without further experimental work. Also, the database is very small and to be generalized for other areas much larger data bases are needed to check the validity of conclusions arrived at during this work. The importance of the present work lies in pinpointing parameters that have strong correlations with other difficult to measure parameters.

PRACTICAL IMPLICATIONS

In case of clean 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 can be used to derive cementation exponent, secondary, matrix and vug porosity, as well as, modified saturation. Water saturation can be obtained from total porosity and modified saturation and consequently fracture porosity may be derived. Fracture porosity can also be calculated by subtracting the sum of matrix and vug porosity from total porosity. Permeability can be estimated from total porosity and cementation exponent using Jorgensen's (1988) equation.

CONCLUSIONS

Despite its limited size, the present database shows that some easily measured parameters can be used in deriving other parameters with correlation coefficients mostly more than 0.9. Thus, Vp can be used to derive sonic porosity and similarly total porosity can give cementation exponent, secondary, matrix and vug porosity, as well as, modified saturation. The latter can be used to derive cementation exponent, secondary and matrix porosities. Degree of saturation is a good indicator of fracture porosity.

There is a need of larger database to check the validity of relationships deduced by the present study and to restrict its use to clean limestone.

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