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Compressive Strength of Vuggy Oolitic Limestones as a Function of Their Porosity and Sound Propagation

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Abstract

Vuggy oolitic limestones have been screened previously based on the determination of their cementation exponent (m) values. The higher the m values above 2, the higher the percentage of separated vugs. Uniaxial compressive strength of 15 French vuggy limestones has been characterized using the velocity of sound and some pore-related properties. The work resulted in 10 equations that predict compressive strength from velocity of sound, saturation coefficient, cementation exponent (m), permeability, and porosity (total, sonic, secondary, matrix, and vug). Practical implications of the present work and its limitations have also been discussed.

Keywords: Uniaxial Compressive Strength; Velocity of Sound; Secondary Porosity; Vug Porosity; Limestone; Oolitic; Petrophysics; Jurassic; France.

1. Introduction

The Many technical and industrial aspects of carbonates are related directly or indirectly to their pore microstructure, which is complicated in comparison to that in the siliclastics (Mazzullo and Chillingarian, 1992). Hence, the amount and type of secondary porosity (relative to total porosity) and its distribution within the rock exert strong control on the usefulness of a carbonate rock as an oil reservoir. Applications include production and stimulation characteristics of carbonate reservoirs (Jordy, 1992; Chillingarian et al., 1992; Hendrickson et al., 1992; Honarpour et al., 1992; Wardlaw, 1996), salt durability (Leary, 1983) and restoration of stone (Ashurst and Dimes, 1990; Spry, 1982).

According to Choquette and Pray (1970), limestone's porosity is either (1) primary with pores occurring between particles or crystals or within them, or formed by gas bubbles and sediment shrinkage (*fenestral porosity*), and as *shelter* or *growth-framework pores* (common in reef buildups); or (2) secondary porosity (Mazzullo, 2004): which is formed by post-depositional dissolution (by freshwater and/or aggressive fluids), or fracturing. Thus, most of the porosity in limestone reservoirs is of secondary origin. Cavernous and associated vuggy porosity present in oolitic 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 & Albrandt, 2002).

Where sophisticated laboratory tests are rarely performed due to high expenses or lack of facilities, there is a need to develop simple estimation schemes by which different porosity types and quantities are defined. This will be of importance for interpretation of geophysical logs at the well site (with none or minimum amount of laboratory work). The present author (Moh'd, 2007) characterized the secondary porosity of some Jordanian building limestones using easily measured properties (total porosity, water saturation and velocity of sound Vp).

Unconfined Compressive Strength (UCS), the most frequently used strength test for rocks is their ability to withstand crushing under direct pressure, as in blocks and columns (Fox, 1923) or *'the stress required to break a loaded sample that is unconfined at its sides'.* (Krynine and Judd, 1957). Carrying out the test usually follows ASTM designation C-170: Compressive strength of building stones and preparation of the test specimens is time consuming. Compressive strength can be defined as the load per unit area at which a block fails by shear or splitting. Test specimens are in the form of cubes or cylinders (with preferably 2:1 length to diameter ratio). The test is usually carried out on dry or saturated samples perpendicular to or parallel to bedding.

Test results are affected by internal and external factors. The former includes mineralogy (especially quartz content, cement type, clay minerals) and fabric; the way in which the crystals are assembled (Price 1960; Lamar 1967; Vutukuri et al. 1974; Dearman 1974 and 1976; Irfan and Dearman 1978; Mogilevskaya 1965), size and shape of grains (Brace 1961; Skinner 1959; Lamar 1967), density and porosity (Attewell and Farmer 1976; Smoradinov et al. 1970; Hoshino 1974), water content (Ruiz 1966; Feda 1966; Korkosky and Husale 1968; Duncan 1969; Parate 1973; Mogilevskaya 1970; Broch 1974, 1979; Boozer et al. 1963; Pugh 1967), temperature (Hawkes and Mellor

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1970; Mellor and Rainey 1968, 1969; Brighenti 1970), and anisotropy (Somerton et al. 1970; Al-Jassar and Hawkins 1979; Stoney and Dhir 1977; Jovanic 1970). External factors are related to the test conditions and include both specimen geometry and testing state. These factors include specimen geometry (aspect ratio (height/diameter, h/d) and size) Hawkes and Mellor, 1970; Vutukuri et al., 1974; Obert and Duvall (1967); Bieniawski 1973; Vutukuri et al. 1974; Hosking and Horino 1986; Hudson and Cook 1970; ISRM 1979), core ends and rate of coring in addition to capping material and loading rate (Obert et al. 1964; Perkins and Green 1970; Houpert 1970).

In a previous paper (Moh'd, 2008), the amount of vug porosity has been estimated in many oolitic limestones including 15 samples representing 8 French building limestones. The present work aims at investigating how the uniaxial compressive strength of these limestones is related to velocity of sound, saturation coefficient and modified saturation, cementation exponent (m), permeability, and the different types of porosity (total, sonic, secondary, matrix, vug).

2. Materials and Methods

The studied stones along with their salient petrographic features have been summarized in Table 1 after Honeyborne (1982). As can be seen in this table, most of the studied stones are oolitic limestones of dominantly Jurassic age. Eight stones with 16 subtypes have been covered in this study.

Table 1. Notes on the studied limestone (modified after Honeyborne, 1982).

Stone name	Description	Sparite / micrite	Sample No.
Savonnieres	Shelly oolitic limestone, average oolite diameter 0.5 mm	sparite	6, 7, 8
Brauvilliers	Oolitic limestone with occasional shell fragments	sparite	9, 10, 11
Anstrude	Bathonian, crinoidal oolitic limestone	micrite	14, 15, 16
Massangis	Oolitic limestone with shell fragments and occasional nodules of silica and/or pyrite	micrite	20
Vilhonneur	Oolitic limestone, oolites fine-medium	sparite	37, 38, 39
Sireuil	Cenomanian, fine-medium, oolitc limestone with quartz microfossils	micrite	40
Terce	Callovian, chalky oolitic limestone, very fine, dominantly microporous with occasional macropores.	micrite	50
Chauvigny	Bathonian, oolitic limestone	sparite	53

The results of compressive strength (on 70 mm cubes), porosity, degree of saturation, and sound velocity (Vp) tests, which were carried out following the French procedures (Mammilan, 1976), were taken from Honeyborne (1982).

Derived properties include:

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

Cementation exponent m: this parameter, which is positively related to the separated vugs as suggested by Lucia (1983), was calculated using Archie formula and assuming that water resistivity as 0.005 (Archie, 1952) 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 = $\Phi^{m+2}/(1-\Phi)^2$. This number (84105) is the proportionality constant in permeability-porosity index equation. 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.

In summary the cementation exponent m has been estimated for each stone type. Then those stones with m more than 2 have been considered of vug porosity. After that, only oolitic limestones with m more than 2 have been dealt with. Oolitic limestones have been identified after consulting the description of each stone in Honeyborne (1982).

3. Results

Properties of vuggy French oolitic limestones taken from Honeyborne (1982) are listed in Table 2, and those derived by the author using the methods applied in the previous section are in Table 3. The different properties are correlated in Table 4. A statistical summary is shown in Tables 5 and 6. Bivariate plots between unconfined compressive strength and other properties are shown in Figures 1 to 10. The results of the work are summarized in Table 7. The relationship between UCS and each variable has been examined by fitting linear, logarithmic, power or exponential equations of the Excel program. The selected relationship shown in Table 7 is the one having the best fit (maximum correlation coefficient r), on one hand, and avoiding negative values of UCS or other variables, on the other (when the curve extended). Equations in Table 7 are arranged (in descending order) based on correlation coefficient r-values.

The studied oolitic limestones range in their compressive strength from 10.4 to 80.2 MPa, thus classified according to Deere and Miller (1966) into very low strength (< 28 MPa, samples 6, 7, 8, 9, 10, and 40), low strength (29-56 MPa, samples 14, 15, 50, 53) and medium strength (56-112, samples 20, 38, 39).

Figure 1 shows that there is an almost perfect (r= 0.983) positive relationship (power function) between compressive strength and dry density. The very strong (r= 0.91) positive exponential relationship between velocity of sound and compressive strength (Figure 2) reveals that the latter can be estimated by the non-destructive sonic velocity test. There seems to be a critical value of velocity at about 4000 m/s above which compressive strength increases rapidly.

A very strong (r= -0.98) negative exponential relationship (Figure 3) occurs between total porosity and compressive strength. Below a critical porosity value of about 25%, compressive strength changes quickly. Figure 4 shows an inverse logarithmic relationship (r= -0.77) between modified saturation and compressive strength. Below a modified saturation value of 15 compressive strength changes rapidly.

Figure 5 shows an inverse relation (r= -0.89) between cementation exponent m value and compressive strength. The higher the percentage of separated vugs (expressed by higher values of cementation exponent m), the lower the compressive strength is. Compressive strength changes rapidly below a cementation exponent value of 3.

Figure 6 shows an inverse relation (r= -0.95) between permeability and compressive strength. The latter drops quickly when the value of permeability reaches 50-60 md, then the rate of strength decrease becomes lower as the permeability increases.

Figure 7 shows an inverse relation (r= -0.91) between uniaxial compressive strength and sonic porosity. Compressive strength changes quickly below a sonic porosity value of about 5%.

Figure 8 shows an inverse relation (r= -0.96) between uniaxial compressive strength and secondary porosity. Compressive strength changes rapidly up to a secondary porosity value of about 16%.

Figure 9 shows an inverse relation (r= -0.92) between uniaxial compressive strength and vuggy porosity. Compressive strength changes rapidly below a vuggy porosity value of about 10%.

Figure 10 shows an inverse linear relation (r= -0.82) between uniaxial compressive strength and matrix porosity.

Table 2. Properties of vuggy French oolitic limestones taken from Honeyborne (1982).

Sample No.	Density (g/cm^3)	Compressive Strength (MPa)	Sound Velocity (m/s)	Porosity (%)	Saturation Coefficient (%)
6	1.721	11.2	2881	36.1	0.52
7	1.748	11.2	2684	34.7	0.5
8	1.82	17	2702	30.6	0.68
9	1.959	23.2	3106	27	0.57
10	1.826	17.6	2966	32.6	0.54
11	1.766	11.9	3045	33.7	0.47
14	2.114	45.6	3376	21.9	0.81
15	2.14	41.1	3374	20.6	0.66
16	2.218	58.1	4282	18.1	0.65
20	2.3	80.2	4276	15.1	0.88
38	2.392	65	4259	11.7	0.94
39	2.389	76	4606	11.9	0.64
40	1.727	10.4	2069	36	0.76
50	2.061	36.2	3332	23.7	0.88
53	2.201	38.3	4014	18.7	0.71

Table 3. Derived properties of vuggy oolitic limestones.

Sample No.	Modified Saturation	Cementation Exponent m	Permeability millidarcies	Sonic Porosity%	Seconday Porosity %	Vug Porosity %	Matrix Porosity %
6	18.77	3.92	494.61	7.2	28.9	22.5	13.6
7	17.35	3.7	473.01	8.1	26.6	22	12.7
8	20.81	3.82	177.42	8.0	22.6	18	12.6
9	15.39	3.19	176.58	6.3	20.7	17	10
10	17.6	3.63	336.45	6.9	25.7	19	13.6
11	15.84	3.48	493.41	6.6	27.2	20	13.7
14	17.74	3.21	30.8	5.4	16.5	13	8.9
15	13.6	2.83	64.74	5.4	15.2	10	10.6
16	11.77	2.6	48.26	3.2	14.9	8.5	9.6
20	13.29	2.67	17.09	3.3	11.9	10	5.1
38	11	2.41	8.39	3.3	8.4	4.1	7.6
39	7.62	2.07	18.72	2.7	9.3	1.25	10.7
40	27.36	4.65	230.08	12.0	24.0	22.5	13.5
50	20.86	3.5	52.59	5.6	18.1	14	9.7
53	13.28	2.75	44.25	3.8	14.9	5.3	13.4

Table 4. A correlation matrix between the different properties.

	Density	Comp. strength	Sound velocity	Porosity	Saturation Coef.	Mod. saturation	m	Permeability	Sonic porosity	Secondary porosity	Vug porosity	Matrix porosity
Density	1.00											
Compressive strength	0.96	1.00										
Sound velocity	0.93	0.92	1.00									
Porosity	-1.00	-0.95	-0.93	1.00								
Saturation coefficient	0.62	0.61	0.39	-0.62	1.00							
Modified saturation	-0.77	-0.73	-0.88	0.77	-0.01	1.00						
m	-0.92	-0.87	-0.96	0.92	-0.28	0.95	1.00					
Permeability	-0.86	-0.80	-0.67	0.87	-0.78	0.40	0.65	1.00				
Sonic porosity	-0.88	-0.84	-0.97	0.88	-0.31	0.90	0.96	0.61	1.00			
Secondary porosity	-0.98	-0.94	-0.86	0.98	-0.69	0.68	0.85	0.91	0.79	1.00		
Vug porosity	-0.97	-0.88	-0.92	0.97	-0.51	0.80	0.92	0.82	0.87	0.95	1.00	
Matrix porosity	-0.74	-0.82	-0.63	0.74	-0.71	0.44	0.60	0.70	0.62	0.75	0.56	1.00

Table 5. Statistical summary of properties tested by Honeyborne (1982).

	Density	Comp. strength	Sound velocity	Porosity	Saturation coefficient
Mean	2.03	36.20	3398.13	24.83	0.68
Standard Error	0.06	6.30	189.76	2.26	0.04
Standard Deviation	0.25	24.40	734.95	8.75	0.15
Range	0.67	69.80	2537	24.40	0.47
Minimum	1.72	10.40	2069	11.70	0.47
Maximum	2.39	80.20	4606	36.10	0.94
Count	15	15	15	15	15

Table 6. Statistical summary of derived properties.

	Modified Saturation	m	Permeability	Sonic porosity	Secondary porosity	Vug porosity	Matrix porosity
Mean	16.15	3.23	177.76	5.84	18.98	13.81	11.02
Standard Error	1.24	0.18	47.79	0.64	1.72	1.82	0.67
Standard Deviation	4.81	0.68	185.08	2.48	6.67	7.04	2.59
Range	19.74	2.58	486.22	9.31	20.47	21.25	8.6
Minimum	7.62	2.07	8.39	2.66	8.42	1.25	5.1
Maximum	27.36	4.65	494.61	11.97	28.89	22.5	13.7
Count	15	15	15	15	15	15	15

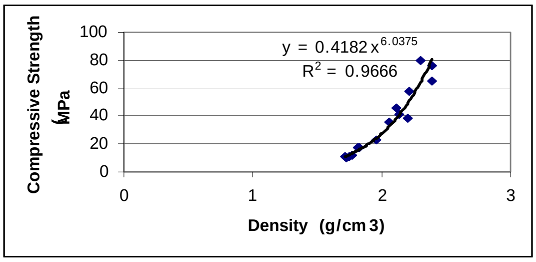

Figure 1. Density versus compressive strength.

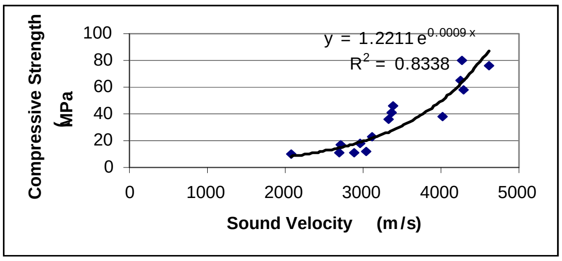

Figure 2. Sound velocity versus compressive strength.

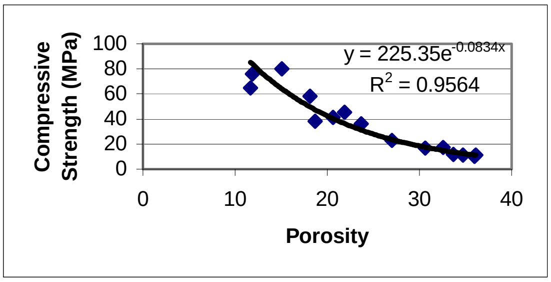

Figure 3. Total porosity versus compressive strength.

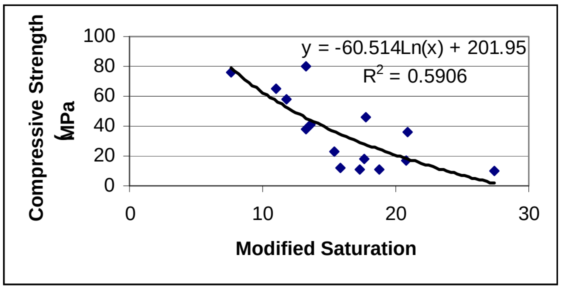

Figure 4. Modified saturation versus compressive strength.

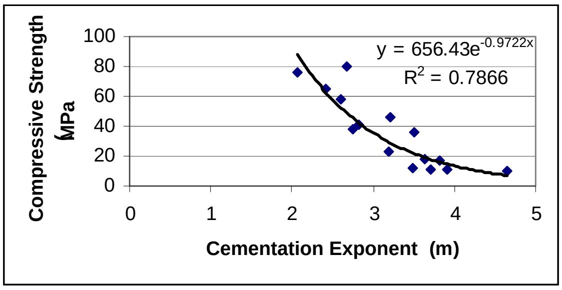

Figure 5. Cementation exponent versus compressive strength.

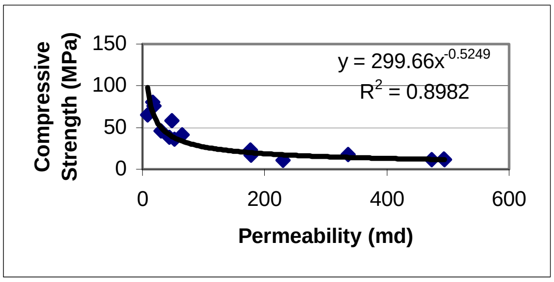

Figure 6. Permeability versus compressive strength.

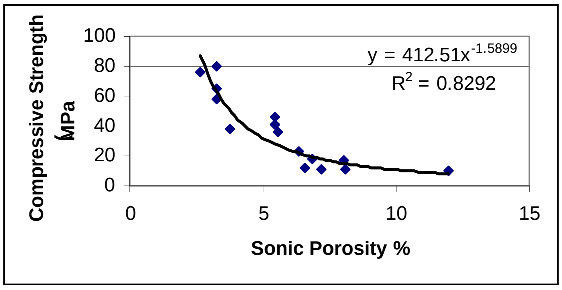

Figure 7. Sonic porosity versus compressive strength.

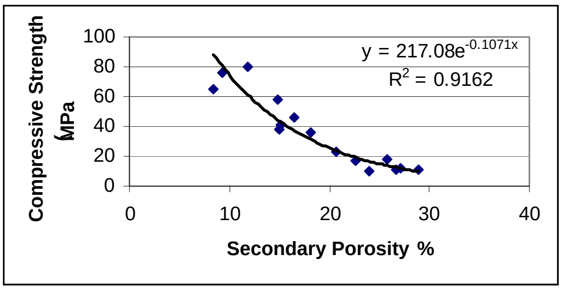

Figure 8. Secondary porosity versus compressive strength.

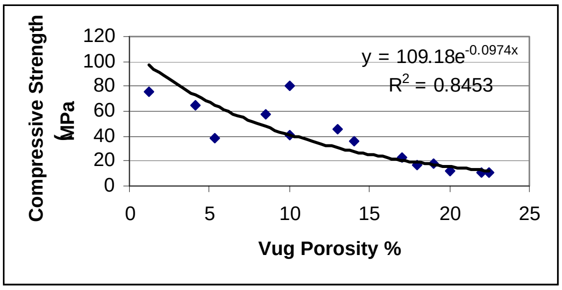

Figure 9. Vug porosity versus compressive strength.

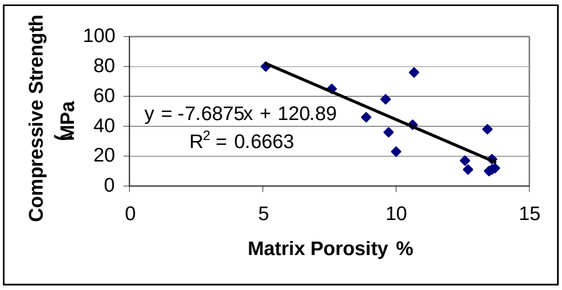

Figure 10. Matrix porosity versus compressive strength.

Table 7. A list of significant relationships between compressive strength and other parameters illustrated in Figures 1 to 10.

Fig.	Equation	R^2	R
1	UCS = 0.4182 density $^{(6.0375)}$	0.9666	+0.9832
2	UCS = 225.35/e $^{(0.0834\text{ porosity})}$	0.9546	-0.9777
3	UCS = 217.08/e $^{1.071\text{ (secondary porosity)}}$	0.9162	-0.9572
4	UCS = 299.66/ permeability$^{0.5249}$	0.8982	-0.9477
5	UCS = 109.18/e$^{0.0974\text{ vuggy porosity}}$	0.8453	-0.9194
6	UCS = 1.2211 e$^{0.0009\text{ (sound velocity)}}$	0.8338	+0.9131
7	UCS = 215.51/sonic porosity($^{1.5899)}$	0.8292	-0.9106
8	UCS = 656.43/e$^{0.9722\text{ (cementation exponent)}}$	0.7866	-0.8869
9	UCS = -7.6875 (matrix porosity) – 120.89	0.6663	-0.8163
10	UCS = -60.514 Ln (modified saturation) + 201.95	0.5906	-0.7685

4. Discussion of Results

In almost all the previous cases the best-fit curve shown represents approximately the average value of compressive strength. Lower and upper envelopes can be made by connecting the lowest points below the curve (lower envelope) and the highest points above the best fit-curve (upper envelope). As it is well known that micrite imparts higher strength to the rock than sparite, it is believed that the upper envelope is related to the highest micrite contents, whereas the lower envelop is related to highest sparite contents. The upper and lower envelopes may also be related to other factors such as mineralogical constituents other than carbonates (e.g. silicification), and vug-size distribution. These points were not tackled in the present work, but indicated the importance of integrating petrographic investigations with any geotechnical study on vuggy oolitic limestone.

The strong relationship between compressive strength and both total porosity and velocity of sound reflects, more or less, homogenous nature of the studied samples. This idea is further supported by plotting the total porosity (on the x-axis) and the sonic velocity (on the y-axis) (Figure 11). In this case the samples will be aggregated and nicely fitted by one straight line (see also Moh'd, 2008). Had the studied suite of samples been of heterogeneous nature, it would have been plotted in the total porosity- sonic velocity graph, as seen in Figure 12 which shows a weak inverse relation and high scattering of data. Figure 12, which includes 47 UK oolitic limestones, was drawn after screening Leary (1982) data. If fitted with one curve, then R^2 is much lower than that shown in Figure 11. This indicates the high complexity of the pore structure of the UK oolitic limestones in comparison to that of the French stones. Unfortunately, compressive strength of these stones was not provided by Leary (1983).

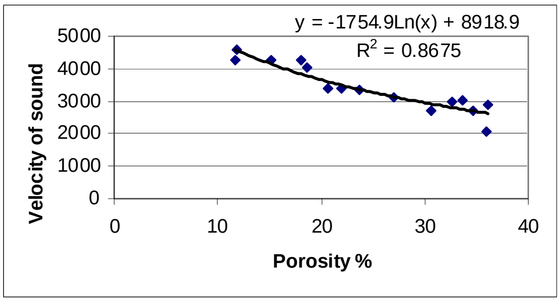

Figure 11 Porosity versus velocity of sound of the studied limestones.

If the vugs presence is ignored, then an idea about the uni- or bimodality of pore space can be gained from the degree of saturation values. The studied suite of rocks has a degree of water saturation ranging from 0.47-0.94. Limestones, having their pore space in the form of finer capillaries, will have high values of water saturation (samples 38, 50, 20). This usually occurs in the micro pores of the vuggy oolitic limestone. When the degree of saturation is less than 0.60, then the pore space is bimodal (have 2 capillaries r and R, samples 6, 7, 9, 10, and 11). The remaining samples are either of unimodal or slightly bimodal pore space (small difference between r and R). This can be further checked by plotting porosity against modified saturation (Bellanger et. al., 1993; Moh'd, 2008). As seen in Figure 4, the compressive strength has a negative relation with modified saturation. Being equivalent to porosity multiplied by saturation, modified saturation can be thought of as equivalent to the amount of water that the limestone can accommodate in its interconnected pore space. This property is referred to as 'bulk volume water' in petrophysics literature.

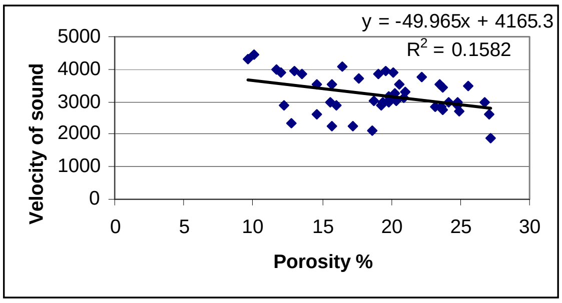

Figure 12. Porosity versus velocity of sound of the UK ooliticlimestones showing weak inverse relation and high scattering of data.

The higher the cementation exponent m value above 2, the higher the proportion of isolated vugs is, and consequently the lower the compressive strength. Vuggy porosity has a relationship with compressive strength similar to that of cementation exponent since cementation exponent is used in deriving vuggy porosity using Aguilera and Aguilera (2003) method.

5. Practical Implications, Limitations and Suggestions

To estimate the uniaxial compressive strength in the case of vuggy oolitic limestone, and when it is difficult to have access to sophisticated equipment, the easiest parameter to measure is dry density, which can be inverted to compressive strength using Figure 1. As a double check, total porosity can be measured (or derived from dry density) to estimate compressive strength using Figure 2.

The number of samples included in the present database is relatively small. Being collected from one region (France), thus possibly reflecting one sedimentary basin may be the reason for the homogenous nature of the studied samples. Consequently, extending the present study to include analyses of larger databases collected from different sedimentary basins may be necessary to show potential heterogeneities.

The suite of rocks studied in this work is predominantly of very low-to-low compressive strength. Results from this work should not be generalized to strong or very strong rocks without further testing. It is believed that the compressive strength of the latter types of rocks will be more affected by the presence of vugs especially if they have a micritic matrix and/or low porosity (e.g. Carboniferous limestones of England). As pointed out in the discussion section, the reason of the scattering of the data points in the different figures may be better understood if the physical and engineering properties are integrated with a petrographic study. Here factors such as micrite and sparite contents, non-calcareous minerals (silicification for instance), type of cements and the nature of their distribution, oolites size and distribution, and fracture-vug relationships and vug size distribution should be emphasized.

6. Conclusions and Recommendations

Compressive strength of the studied samples has positive relationships with density and sonic velocity and inverse relationships with permeability, modified saturation, total and other porosity types. This parameter can be derived from dry density alone. It can also be estimated from the knowledge of porosity types and amounts with accuracy decreasing in the following order: total porosity, secondary porosity, vuggy porosity, sonic porosity and matrix porosity. From a practical point of view, dry density, which is the easiest parameter to measure, can be used for predicting compressive strength. Carrying out a study including vuggy oolitic limestones spanning the whole range of strength (very low to extremely strong), and integrated with petrographic investigations is highly recommended.

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Compressive strength of vuggy oolitic limestones as a function of their porosity and sound propagation. Article. Jan 2009. B.K. Moh'd. View. The effect of pore size on tensile and compressive strengths of rock: A bonded particle simulation. Article. Jan 2011.Â Uniaxial compressive strength of 15 French vuggy limestones has been characterized using the velocity of sound and some pore-related properties. The work resulted in 10 equations that predict compressive strength from velocity of sound, saturation coefficient, cementation exponent (m), permeability, and porosity (total, sonic, secondary, matrix, and vug). Practical implications of the present work and its limitations have also been discussed. View. ISSN 1995-6681 Pages 18-25 Jordan Journal of Earth and Environmental Sciences Compressive Strength of Vuggy Oolitic Limestones as a Function of Their Porosity and Sound Propagation Basem K. Mohd *. Tafila Technical University (TTU), Tafila, Jordan Abstract Vuggy oolitic limestones have been screened previously based on the determination of their cementation exponent (m) values.Â Uniaxial compressive strength of 15 French vuggy limestones has been characterized using the velocity of sound and some pore-related properties. The work resulted in 10 equations that predict compressive strength from velocity of sound, saturation coefficient, cementation exponent (m), permeability, and porosity (total, sonic, secondary, matrix, and vug). Compressive strength of vuggy oolitic limestones as a function of their porosity and sound propagation. Article. Jan 2009. B.K. Moh'd. View. The evolution of travertine masses in the Sivas area (Central Turkey) and their relationships to active tectonics. Article. Full-text available.Â This discrepancy is explained by rock texture variations, which influence the fracture propagation mode and consequently fracture initiation stress. The quantification of rock texture is accomplished using porosity. Fracture initiation stress is shown to be inversely related to both porosity and mean grain size.