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Determination of the Cementation and Tortuosity Factors for Sandstones from Girei Local Government Area, Adamawa State, Nigeria

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ABSTRACT: This study presents the results of the cementation and tortuosity factors for sandstones from Girei, part of the Yola arm of the Upper Benue Trough. It also presents the cementation factor for the individual/single rock samples using an experimentally determined value of the tortuosity factor. The cementation factor values were then compared with that obtained using an assumed value, in order to test the reliability or otherwise of using an assumed value of the tortuosity factor for cementation factor calculation irrespective of the formation of interest. Results of the cementation exponent and tortuosity factor for fourteen representative surface rock samples from the Girei sandstones were 3.73 and 1.39 respectively, indicating that the rocks are highly cemented and may contain clay which increases the value of the cementation factor. The cementation factor for each rock sample varied between 2.77± 25.74% and 5.42 ± 45.31% with an average of 3.96 ± 6.17% when the tortuosity factor is obtained from experiment and 2.94 ± 21.18% - 6.78 ± 54.96% with an average of 4.01 ± 7.51% when obtained with an assumed tortuosity factor of 1.0. The average value of the cementation factor calculated when the toruosity factor was obtained from experiment agrees more with the experimentally determined value. This showed that whenever the value of the cementation factor for each sample is required, an experimentally determined value of the tortuosity factor should be used rather than an assumed value.

Key words: Cementation factor, Tortuosity factor, Formation factor, Resistivity, Porosity.

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INTRODUCTION:

The cementation factor (m) of Archie's equation is one of the parameters used in the detection and evaluation of subsurface hydrocarbon or water accumulation. It indicates reduction in the number and size of pore openings or reduction in the closed-off (dead-end) channels and so it varies with the degree of cementation of the rocks. It has been widely used in hydrocarbon and ground water exploration, and in porous media engineering studies (Archie, 1942; Winsauer *et al.,* 1952; Donalson and Siddigui, 1989; Salem, 1992). The use of incorrect values of m can lead to overlooking producible zones or the completion of poor zones. Frequently, assumptions are made to approximate m and often times the value of 2 or 2.15are used without considering the lithiology under investigation. Generally, the cementation factor exhibits wide variations from sample to sample, formation to formation, interval to interval in the same medium and from medium to medium (Winsauer *et al*,1952; Porters and Carothers, 1970; Olafuyi and Omole 2010. Archie (1942) obtained a value of 2 for the Gulf Coast, Winsauer *et al* (1952) obtained a value of 2.15 from North American sandstones, Porters and Carothers (1970) obtained values of 1.29 for Miocene sands from Texas and 1.08 for Pliocene sands from California and Olafuyi and

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Omole (2010) obtained a value 1.41 for the Central offshore of the Niger Delta. Wyllie and Rose (1950) stated that *m* can vary in the mathematical sense between one and infinity, but practically, it lies within the limits of 1.3 and 3. Keller (1982) as quoted by Schon (1996) summarized different values of *m*, showing that *m* is affected by lithology, porosity, degree of compaction and cementation, and age. Salem and Chilingarian (1999) stated that *m* generally varies between slightly less than one for fractured rocks and 5.12 for well consolidated and highly compacted rocks. In addition, the cementation factor (*m)* and tortuosity factor (*a)* are affected by shape of grains and pores, type of grains, type of pores, specific surface area, tortuosity, anisotropy and overburden pressure (compaction). The cementation exponent also has specific effects on electrical conductivity processes in porous media.

Different methods exist for the determination of the cementation factor. These include: laboratory core analysis measurements which requires laboratory measurements of electrical resistance and porosity; calculating *m*, assuming *a* where *m* is obtained for a single rock sample; and using well log data. In this study, laboratory measurement was first used to determine *m* for the whole formation after which *m* was determined for each rock sample studied.

As stated above, the values of *a* and *m* vary from formation to formation and from location to location. This research therefore aims at obtaining the values of these parameters for Girei sandstones hence providing a firsthand data base that can be useful to researchers on this subject. Furthermore, the research aims at obtaining *m* for each rock sample studied and then investigate the reliability or otherwise of using an assumed value of *a* to determine *m* irrespective of the formation under investigation.

Location and Geology of the Study Area

Girei Local Government Area used for this study lies between latitude $9^0 00$'N and $9^0 32$'N and longitude $12^0 10$'E and $12^0 48$'E (figure 1). The study area is part of the Yola arm of the upper Benue trough and is composed mainly of the Bima sandstone formation and quaternary river coarse alluvium. The Bima sandstone comprises of the oldest sediments in the upper Benue trough which directly overlie the crystalline basement rocks. Carter *et al.* (1963) and Allix (1983) gave descriptions of the sequence exposed there and recognized a three fold subdivisions; namely; the upper Bima (B3), the middle Bima (B2) and the lower Bima (B1).

The upper Bima is fairly homogenous, relatively mature, and fine to coarse-grained, thick-bedded sandstone with abundance of sedimentary structures. It is widespread and may attain more than 1700m in thickness. The sequence was deposited under fluvatile to deltaic environment (Carter *et al.*, 1963). The late Albian to early Cenomanian age is assigned to this upper member (Whiteman, 1982).

The middle Bima (B2) is a fairly uniform unit composed of very coarse-grained, feldspathic sandstone with thin Bands of clay, silts, shale and occasional calcareous sandstone. It varies in thickness from 300m to 1200m. A tentative middle Albian age has been assigned to it by Whiteman (1982) on the basis of pollens and radiometric data obtained from intercalated lavas.

Lower Bima appear in the core of the Lamurde anticline where they consists of coarse- grained feldspathic sandstone alternating with red, purple shale and occasional bands of calcareous sandstone and siltstone. It is a highly variable unit with an overall thickness of over 500m. An upper Aptian/Albian age has been assigned to this part of Bima sandstone (Kogbe, 1989).

Field study of the gully sites revealed that the Bima sandstones has been moderately weathered, moderately sorted, loosed and contains small portions of clays. The alluvial deposit which occurs mainly along the banks of the River Benue and its tributaries consists of sands, clays, silts, silty-clays and pebble sands (Offodile, 1982). The sands are usually loose, moderately sorted and relatively permeable.

Figure 1: Map of study Area showing sample locations

Theory

Electrical current conductivity in porous media or rock-bearing water is controlled by various mechanisms. The most important mechanisms are the pore fluid (ionic or electrolytic) conductivity and the fluid solid (surface) conductivity (Salem and Chilingrian, 1999 and Attia *et al.*, 2008). The electrolytic conductivity depends on the fluid conductivity which is affected by the ionic composition (salinity), ionic exchange capacity of the solid matrix and the acidity and alkalinity of the pore fluid. The surface conductivity mechanism depends on the clay conductivity which is affected by the content and type of clay, and the charged ions concentrating at the grain boundaries. When the pore fluid has a low concentration of ions (fresh water), the surface conductivity becomes predominant in the process of electric current conduction. When the pores are saturated with saline water, the electrolytic conduction becomes predominant, because the conduction of electric current takes place through the saline water (Salem, 1992).

The analyses of the relationship between the rock conductivity/resistivity and the electrolyte conductivity are the subjects of Archie's equation. In 1942, Archie established experimentally that the resistivity of each brine saturated core sample (R_o) increased linearly with the resistivity of the brine (R_W). That is

$$R_o \propto R_W \qquad (1)$$

So that

$$R_o = F_R \, R_W \qquad (2)$$

Where is the constant of proportionality known as the rocks formation resistivity factor. expresses the difference in resistivity value between the brine and brine saturated rock resulting from the presence of a non conductive matrix (formation). The rock formation resistivity factor is a function of porosity, permeability, tortuosity, formation resistivity or the rock's resistivity, lithology, texture, pore water resistivity, salinity, viscosity, density, saturation, clay content, degrees of compaction, cation exchange capacity and uniformity coefficients. The uniformity coefficient embodies the effects of size shape, distribution, packing and sorting of grains (Salem, 1992). It should be noted that the tortuosity factor, a constant in Archie's equation determines the pore geometry and is different from tortuosity which is the ratio of the actual or effective length of a flow path to the length of a porous medium, parallel to the over all direction of flow.

Archie further showed that the rock formation resistivity factor and porosity are related by:

(3)

This equation was later modified by Winsauer *et al* (1952) to the general form as

(4)

Where a is the tortuosity factor. Thus, while Archie obtained $a = 1$and $m = 2$, Winsauer *et al* obtained $a = 0.62$ and $m = 2.15$. The differences in a and m obtained by the two researchers is mainly due to the differences in lithology, location, porosity, degree of compaction and age of the rock formation studied.

METHODS OF INVESTIGATION/ SAMPLE COLLECTION AND PREPARATION

Fourteen representative surface rock samples labeled S-$_1$-S$_{14}$ were collected from different locations in the study area. The samples locations were determined using a 12 Channel Garmin Global Positioning System (GPS 12). The *et al.* (2000) was adopted for sample preparation. Firstly, the samples were cut into rectangular shapes, each with a cross sectional area of 2cm by 2cm and a thickness of 1.5cm. This is to ensure accurate determination of their dimensions that will be useful in resistivity calculations. Thereafter, a lapping disk machine (or shaping-up rock machine) was used to smoothen the surface of the rock samples for good electrode contact.

Each sample was then placed in a beaker containing about 400ml of boreholes water labeled Sw$_1$-Sw$_{14}$ obtained from the study area to saturate them for 48hours. A brief description of the sample types, locations, and positions are shown in the Table 1.

Porosity Measurements

The effective porosity which refers to the fraction of the total volume in which fluid flow is effectively taking placed was measured in this study. The American Petroleum Institute (API, 1960) recommended practice for core-analysis procedures have been followed for effective porosity measurements. The procedures routinely used in our measurements are described in the literature [e.g. Katsube and Scromeda (1991), Scromeda and Katsube (1994), Scromeda-Perez and Connell (2001)].

Electrical Resistivity Measurements

Following standard procedures applied by Connell *et al.* (2000) and Scromeda *et al.* (2000), the electrical resistivity (R_o) of the rocks at 100% water saturation was measured at 24 and 48 hours after vacuum saturation with boreholes water and the mean taken. This was to ensure that the electrical resistivity values were stable with time. Under this state, it is expected that the water has chemically equilibrated with the rock

Table 1: Table showing samples description and location

Sample	Description	Location	Latitude	Longitude
S_1	Very fine-grained sandstone	Wuro Ngolirde	$9^0$26’28.3"N	$12^0$34’07.0"E
S-$_2$	Fine-grained sandstone	Wuro Labai	$9^0$30’14.9"N	$12^0$39’22.7"E
S_3	Limonitic feldspathic coarse-grained sandstone	Jabbi Lamba	$9^0$30’17.8"N	$12^0$36’15.1"E
S_4	Weathered conglomerate	Nasarawo	$9^0$31’22.7"N	$12^0$33’47.6"E
S_5	Weathered coarse-grained sandstone	Mallam Madugu	$9^0$31’12.4"N	$12^0$34’11.5"E
S_6	Limonitic medium-grained sandstone	Wuro Yolde	$9^0$30’46.8"N	$12^0$34’30.0"E
S_7	Limonitic coarse-grained sandstone	Tambo	$9^0$29’59.8"N	$12^0$20’59.9"E
S_8	Slightly ferrigenise coarse-grained sandstone	Jimoh	$9^0$29’12.7"N	$12^0$23’05.7"E
S_9	Feldspatic ferrigenous sandstone	Jera Bonyo	$9^0$29’40.9"N	$12^0$26’54.2"E
S_{10}	Fine-grained sandstone	Wuro Hamsani	$9^0$31’27.8"N	$12^0$31’50.5"E
S_{11}	Medium-grained sandstone	Sabere	$9^0$23’53.4"N	$12^0$33’26.2"E
S_{12}	Coarse-gritty sandstone	Girei	$9^0$21’09.1"N	$12^0$31’46.8"E
S_{13}	Medium-grained sandstone	Sangere (FUTY)	$9^0$19’47.4"N	$12^0$29’47.3"E
S_{14}	Coarse-grained sandstone	Vaniklang	$9^0$18’18.8"N	$12^0$28’46.0"E

and represents in situ conditions. The experimental method used is the two electrode method as it has been described by Telford *et al.* (1978).The resistivity of water samples R_W was obtained by measuring the conductivity of the water samples at 35°C using a conductivity meter and the reciprocal taken.

Determination of *m* and *a*

Equation 4 can be linearized using logarithms as follows

$$\log F_R = -m \log \emptyset + \log a$$

5)

With log F_R plotted against log$\emptyset$, the value of the cementation factor (*m*) is obtained from the slope of the graph while the tortuosity factor (*a*) is also obtained from the intercept on the log axis.

The above method gives a single or average value of *m* and *a,* for rocks in the formation studied. However, to obtain values of *m* for each rock sample studied based on Archie’s equation, the method used by Salem and Chilingarian (1999) was adopted. From equation 4,

(6)

To use equation 6, *a* is usually assumed or obtained as the intercept of the line of best fit of the – relationship (Wyllie, 1957) as quoted by Salem and Chilingarian (1999). In this study, both cases were examined. Firstly *m* was calculated using the value obtained from the plot and labeled m_1. Secondly, *m* was obtained with *a* assumed to be 1.0 (Archie, 1942) and labeled m_2.

RESULTS AND DISCUSSION

Table 2 shows electrical resistivity values for the saturated rock samples, R_o formation resistivity factor, F_R resistivity of water used for saturating the rocks, R_W and the samples porosity,. Porosity values ranges from 11.9-27.9% (0.12-0.28). R_W values were in the range of 1.01-26.32 &!m (0.04-0.99 mho). F_R ranges from 161.95-6852.56 while R_o ranges from 7.485 X 10^3-10.690 X 10^3 &!m with an average of 8.160 ± 0.229 x10^3 &!m. A plot of logarithm of F_R against logarithm of used to obtain the cementation exponent, *m* and tortuosity factor, *a* is shown in figure 2. An approximately inverse relationship was found to exist between F_R and.

The graph also shows a low correlation coefficient R^2 of 0.5213. To obtain a better R^2, a large range of porosity and formation resistivity factor is required. The results obtained showed that the values of *m* and *a* were 3.73 and 1.39 respectively. Hence, Archie's equation for sandstones in Girei was therefore found to be;

The value of *m* obtained may be said to be high when compared with that obtained by Archie, (1942) and Winsauer *et al.*, (1952). This high value may indicate abundance of clays since the rocks were not cleaned and presence of clay usually increases resistivity which in turn increases *m*. The high *m* value may also be attributed to the presence of complicated porosity types and/or high degree of irregularity of grains. Increase in consolidation, compaction and cementation causes a decrease in porosity and an increase in the degree of irregularity of grains resulting in higher values of *m*. *m* values are dominated by the presence of cement; hence the high value of *m* may also suggest that the rocks are highly cemented. The value of *m* obtained falls within the range stated by Salem and Chilingarian (1999).

The age of the rocks also plays an important role in the value of the cementation factor. The older the rock, the higher the cementation factor and vice versa. This is clearly shown in the work of Porters and Carothers (1970) who obtained 1.29 and 1.08 as values of *m* for Miocene sands and Pliocene sands respectively. The high value of *m* obtained for the rocks studied may also be attributed to their age which ranges from the Aptian to the Cenomanian. Geologically, these rocks are older than the ones Porters and Carothers (1970) used for their studies and so a higher *m* values are expected.

m =3.73 n = 1.39

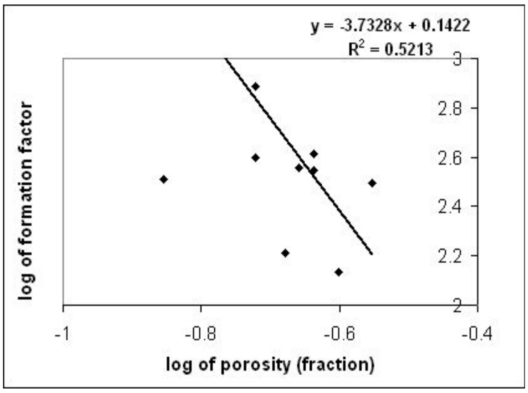

Figure 2: Graph used for obtaining *m* and *a*

Table 2: table showing conductivity of saturating water samples ($_w$), electrical resistivity for saturated samples (R_o), formation resistivity factor (F_R), Resistivity of saturating water samples (R_W) and porosity ($\varnothing$)

Sample	$_w$(mho)	R_W (m)	R_o X10^3(m)	F_R	Log F_R	$\varnothing$(faction)	log $\varnothing$
S_1	0.046	21.739	7.817±0.198	359.58	2.556	0.22	-0.658
S_2	0.044	22.727	7.890±0.261	351.12	2.545	0.23	-0.638
S_3	0.640	1.560	10.690±1.485	6825.56	3.835	0.15	-0.854
S_4	0.520	1.920	7.674±0.191	3990.58	3.601	0.23	-0.638
S_5	0.180	5.560	7.560±0.039	1396.80	3.134	0.25	-0.602
S_6	0.099	10.100	7.824±0.303	774.15	2.889	0.19	-0.721
S_7	0.038	26.320	8.562±0.963	325.36	2.512	0.14	-0.854
S_8	0.019	52.910	8.569±0.684	161.95	2.209	0.21	-0.678
S_9	0.990	1.010	7.485±0.115	7410.15	3.870	0.13	-0.886
S_{10}	0.050	20.000	8.160±0.012	408.00	2.611	0.23	-0.638
S_{11}	0.049	20.41	8.050±0.331	394.45	2.596	0.19	-0.721
S_{12}	0.481	2.080	7.975±0.174	3834.14	3.584	0.17	-0.770
S_{13}	0.270	3.700	8.118±0.410	2914.05	3.341	0.12	-0.921
S_{14}	0.040	25.000	7.774±0.155	310.96	2.493	0.28	-0.553

Furthermore, variability of the value of the cementation factor and tortuosity factor obtained for the Girei sandstone formation from that obtained by other researchers in other formations further support the fact that these parameters (cementation factor and tortuosity factor) are not constant but varies from formation to formation depending on formation lithology, pore channel geometry and therefore, textural properties. This means that in order to apply the value of cementation factor in well log interpretation to determining water saturation/ oil saturation in any location, it is needful that an experimentally determined value for the formation of interest is used otherwise wrong results will be obtained. The value obtained here for *a* falls within the range published in literatures (Telford *et al.*, 1978; Lowrie 2002).

Table 3 shows the values of cementation factor calculated for the individual rock samples based on Archie's equation with *a* obtained form experiment and that calculated with *a* assumed to be 1.0. The results showed that the cementation factor, *m* for each rock sample studied varied between 2.77 ± 25.74% and 5.42 ± 45.31%, with an average of 3.96 ± 6.17% when *a* was obtained from experiment and 2.94 ± 21.18% - 5.78 ± 54.96% with an average of 4.01 ± 7.51% when *a* was assumed to be 1.0. From this result, it was observed that the values of *m* computed when *a* was obtained from experiment (m_1) were more accurate than those computed with an assumed value of *a* (m_2), since m_1 gave values that are close to that obtained from experiment (3.73 ± 0.17) with a lower percentage error of about ± 6.17%. Again this has shown that given other parameters (formation resistivity factor and porosity), an assumed value for the tortuosity factor cannot give accurate *m* values for all lithologies, hence the need to seek for an experimentally determined value of *a* for a particular rock formation of interest whenever calculation of *m* is intended. The values of *m* and *a* obtained can be applied to the Bima sandstone formation and other similar formations (if other data were not available).

Table 3: Table showing values of m_1 and m_2, for the individual rock samples

Sample	m_1	**□(%)**	m_2	**□(%)**
S_1	3.67	1.61	3.89	4.29
S_2	3.77	1.07	3.99	6.97
S_3	4.32	15.82	4.49	2.38
S_4	5.42	45.31	5.64	51.21
S_5	4.97	33.24	5.21	39.68
S_6	3.81	2.15	4.01	7.51
S_7	2.77	25.74	2.94	21.68
S_8	3.05	18.23	3.26	12.60
S_9	4.21	12.87	5.78	54.96
S_{10}	3.87	3.75	4.09	9.65
S_{11}	3.40	8.85	3.60	3.49
S_{12}	4.47	19.84	4.66	24.93
S_{13}	3.47	4.56	3.63	2.68
S_{14}	4.25	13.94	4.51	20.91

From the results it can also be seen that the values of *m* obtained in both cases differ from one sample to the other. This may be due to the variation of the individual rock properties such as size and shape of grains, porosity, and tortuosity.

CONCLUSIONS

The cementation factor in the Archie's equation has been widely used in hydrocarbon and ground water exploration, and in porous media engineering studies. The use of incorrect values of *m* can lead to overlooking producible zones or the completion of poor zones. As a result, it has received considerable attention from researchers working in porous media especially, since its value is not constant but varies from location to location and from lithology to lithology. In this study the value of *m* and *a* for the Girei sandstone which is part of the Bima sandstone formation have been determined using the laboratory core analysis measurements. The value of *m* and *a* was found to be 3.73 and 1.73 respectively. This value can be used in the application of similar formation (if other data were not available). The variations of *m* from formation to formation and from sample to sample etc are attributed to several factors such as heterogeneity and compaction of rocks, clay content, irregularity of grains, type of porosity, tortuosity, rock formation resistivity, pore water resistivity and anisotropy.

The value of *m* obtained for each rock sample studied varied between 2.77 ± 25.74% and 5.42 ± 45.31%, with an average of 3.96 ± 6.17% when *a* was obtained from experiment and 2.94 ± 21.18% - 5.78 ± 54.96% with an average of 4.01 ± 7.51% when *a* was assumed to be 1.0. The variation of *m* from one sample to the other may be due to the variation of the individual rock properties such as size and shape of grains, porosity, and tortuosity. It was found that to obtain *m* for a rock sample, the value of *a* required for the calculation should be an experimentally determined value for the particular rock formation of interest.

RECOMMENDATION

This research should be extended to other parts of the Bima sandstone formation in other to have the exact value of the cementation and tortuoisty factors for the formation.

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