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EFFECT OF ELECTRICAL RESISTIVITY MEASUREMENTS ON ARCHIE'S SATURATION EXPONENT.

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ABSTRACT: The effect of laboratory procedures on Archie's saturation exponent *n* using partially saturated rock samples from Girei, part of the Yola arm of the Upper Benue trough has been investigated. Various laboratory procedures affect the value of Archie's saturation exponent *n* for rock samples in a given formation. This paper investigated the effect of electrical resistance measurements on the value of *n* during the brine saturation process rather than during desaturation. Electrical resistivity measurements of the rock samples were performed during the saturation process using two electrode method. Results showed that the saturation exponent, *n* for the rock samples studied varied between 0.50 and 1.56 with an average of 0.72 ± 0.08. The mean value obtained was less than the mean value for clean water wet samples ($n \approx 2$) obtained during de-saturation process, showing that when electrical resistance measurement is performed during saturation process the value of *n* is less than 2. Results also showed that resistivity index, I varies inversely as water saturation S_w. Investigation of the relationship between water saturation and saturation exponent showed that the rocks displayed characteristics typical of rocks having macropores and rough textures.

INTRODUCTION

In 1942, Archie published the results of his investigations on the relationship of the formation resistivity and certain physical properties of a reservoir rock. He posed a challenge to develop methods and relationships that could be used in the quantitative application of electrical resistivity log data in the detection and evaluation of a sub surface hydrocarbon accumulation. He reasoned that in order to be able to recognize a reservoir containing hydrocarbon and connate water, it is necessary to be able to recognize the resistivity of a formation when all its pores are filled with connate water ($S_W = 100\%$). Without this understanding, it would not be possible to appreciate the resistivity added to a formation when some connate water in the pore system of a reservoir rock is replaced by hydrocarbon. From his experiment on electrical conduction in clean sandstones, he established that the resistivity of each brine saturated rock R_o is proportional to the resistivity of the brine R_W .

$$R_o = F_R R_W \qquad 1$$

Archie further considered partially saturated hydrocarbon-bearing 'clean' sandstones, the resulting rock resistivity; R_t will be higher than the brine saturated case (R_o). This is expressed by the resistivity index (I)

$$R_t = IR_O \qquad 2$$

where R_t is the resistivity of the partially saturated rock. The resistivity index depends on the water saturation (S_w) following an empirical relationship derived also from a logarithmic plot of I vs S_w.

$$I = \frac{1}{Sw^n} \qquad 3$$

where *n* is the saturation exponent. Usually $n \approx 2.0$ for water wet rocks (Archie, 1942). It has been found (Schon, 1996, Worthington *et al*, 1992) that it is an unreasonable value to use since it varies. Variations from the mean value $n \approx 2.0$ are variously attributed to the influence of wettability, the nature of desaturating fluid and laboratory procedure (core sample preparation, pressure and temperature). Adisoemarta et al, (2001) stated that *n* ranges from 1 to over 20 for strongly oil wet rocks.

In the water- wet case, water adheres to grain surfaces and builds up a more or less continuous phase in the rock, therefore conducting the current. But in the oil- wet case, the non conducting oil becomes the continuous fluid phase, and the water occurs mostly as isolated droplets. In this case the resistivity is much higher and the saturation exponent increases. Hence the saturation exponent is controlled by the distribution of the conducting brine in the pore space and thus, depends on the rock texture, wetting properties and saturation history caused by capillary effect (Schon, 1996).

Therefore, different saturating techniques and techniques of core sample preparation (coring, cleaning) also have an effect on the laboratory determined saturation exponent (Schon, 1996). Generally, the core sample is 100% saturated with brine water followed by a desaturation process. As the sample is desaturated, electrical resistance is measured at each point. In this study, the electrical resistance is measured during the saturation process.

This study investigated the effect of saturation techniques on the determination of Archie's saturation exponent using sandstones from Girei Local Government Area, Adamawa State, North-Eastern Nigeria. The study becomes important given the fact that *n* is an important parameter in water saturation calculation. The value of the saturation exponent *n* also provides valuable information that is used in hydrocarbon and groundwater exploration. Therefore, the wrong use of *n* can lead to overlooking or overestimation of a producible zone.

GEOLOGY OF THE STUDY AREA

Girei Local Government Area lies between latitude $9^0$00'N and $9^0$32'N and longitude $12^0$10'E and $12^0$48'E (Figure 1.0). 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 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, 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 0 to over 500m. An upper Aptian/Albian age has been assigned to this part of Bima sandstone (Kogbe, 1979).
Field study of the gully sites revealed that the Bima sandstones has been moderately weathered, moderately sorted, loosed and contains small portions of clays (Offodile,1982). The alluvial deposit which occurs mainly along the banks of the River Benue and its tributaries consist of sands, clays, silts, silty-clays and pebble sands. The sands are usually loose, moderately sorted and relatively permeable.

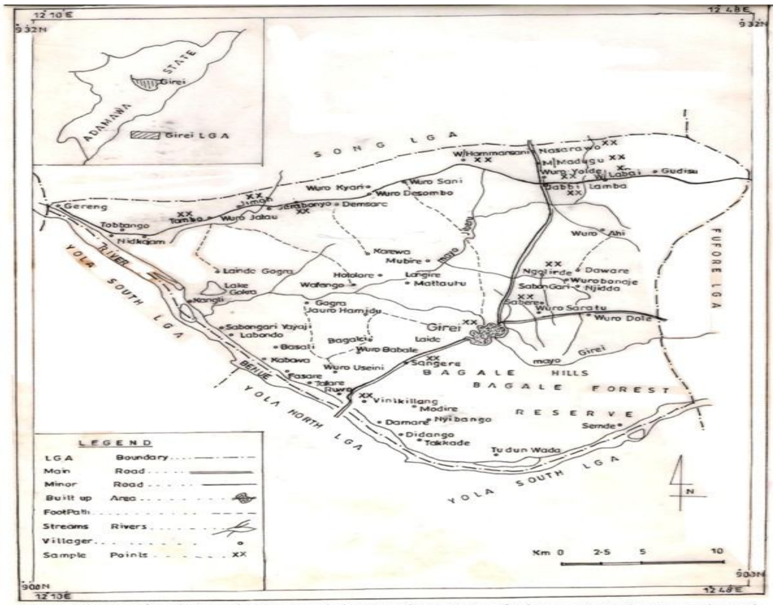

Figure 1.0: Map of study Area showing sample locations (Insert: Map of Adamawa State showing study area)

METHODOLOGY

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 Global Positioning System (GPS). The method used by Scromeda *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. Thereafter, a lapping disk machine (or shaping-up rock machine) was used to smoothen the surface for good electrode contact during resistivity measurements.

A description of the sample types, locations, and positions are shown in Table 1.

Table 1.0**: S**ample 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

Electrical Resistivity Measurements

Laboratory measurements of the electrical resistivity of the rock samples were performed using the two electrode method described by Telford *et al* (1978) and Contreras *et al* (1986). The electrical resistivity measurement of the partially saturated rocks R_t was done at every 3 hours for 48 hours, while the resistivity measurements for the fully saturated rocks R_o was done at 24 and 48 hours of water saturation and the mean taken (Connell *et al*, 2000 and Scromeda *et al*, 2000). 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 and represents insitu conditions.

Measurement of Water Saturation

The total water saturation can be calculated with the formula:

$$S_W = \frac{1oo(W-D)}{D} \qquad 4$$

where S_W is the water saturation, W is the mass of the saturated sample in grammes and D is mass of the dried sample in grammes. Water saturation measurements were done at every 3 hours for 48 hours.

Calculation of *n*

Equation 3 can be linearized by taking the logarithm as follows

$$\log I = -n \log S_W \qquad 5$$

Where $I = {}^{R_t}/_{R_o}$ is the resistivity index and R_t is the resistivity of the rocks at various water saturation. The graph of log I against log S_w yields a negative slope which is equal to *n*.

RESULTS

Values of water saturation, S_W resistivity of the rock samples at various levels of water saturation, R_t and rsistivity index, I are shown in Tables 2.0 to 15.0. Typical plots of resistivity index versus water saturation used to obtain the saturation exponent, *n* for the fourteen rock samples are shown in figures 2.0 to 15.0 results showed that *n* ranges from 0.50 to 1.56. Figure 16.0 shows results of variation of degree of water saturation with saturation exponents.

DISCUSSION

The values of water saturation, S_W and resistivity, R_t at various levels for each sample displayed (Tables 2 to 15) showed that R_t decreases with increasing water saturation for each sample. Decrease in R_t also results in decreasing values of saturation index, I showing that saturation index depends largely on R_t and R_o. Determination of saturation exponents, *n* for the various samples (Figures 2 to 15) gave values of *n* ranging from 0.50 to 1.56 with an average of 0.72 ± 0.08. The values obtained were less than the mean value for water wet samples ($n \approx 2$). Departure from the mean is attributed mainly to the laboratory procedure adopted in the measurement of electrical resistance from where the electrical resistivity used for saturation index calculation was obtained. This showed that the mean value of 2 is correct only for sandstone whose electrical resistance is measured during the desaturating process and not otherwise. This study showed that measuring electrical resistance during the saturation process decreases the value of *n* for water wet rocks. It is established (Schon, 1996 and Adisoemarta *et al*, 2001) that rocks that are not clean increases the value of *n* therefore, high *n* values was expected since the rocks studied were not clean. It can be said here that the influence of cleaning is less than saturation/desaturation effects and so more attention has to be given to saturation/desaturation techniques in the accurate determination of *n*. Besides the measurement method, other factors (which are under investigation) also affect *n*, and might have contributed to the low *n* values. They include influence of wettability, the nature of saturating fluid, the distribution of the conducting brine/fluid in the pore space and the rock texture. Usually lower water saturation results in high resistivity and hence high *n* value while higher water saturation leads to lower resistivity and small *n*.

From the plots shown in Figures 2 -15, it was also observed that resistivity index, I decreases with increasing water saturation, S_W. There was a good correlation between I and S_W for all the samples, having correlation coefficients, R^2 between 0.5783 – 0.9681. Investigation of the relationship between water saturation with saturation exponent (Figure 16) showed an inverse relationship. This displayed typical characteristics of rocks with macropores and rough textures resulting from the heterogenous brine distribution during the saturation process.

Table 2: Resistivity at various levels of water saturation (R_t), water saturation (S_w) and saturation index (I) used for the determination of n for S_1.

Time (Hrs)	**V (volts)**	**I (mA)**	**r_s X10^5 (Ω)**	**Dry weight (g)**	**Wet weight (g)**	**R_t X 10^3 (Ωm)**	**R_o X10^3 (Ωm)**	**I**	**S_w (%)**
3	1100.00	3.55±0.03	3.099	17.72	19.30	8.263±0.022	7.817	1.057	8.92
6	1100.00	3.55±0.02	3.099	17.72	19.30	8.263±0.022	7.817	1.057	8.92
9	1100.00	3.60±0.03	3.056	17.72	19.32	8.148±0.023	7.817	1.042	9.03
12	1100.00	3.6 ±0.01	3.047	17.72	19.33	8.125±0.024	7.817	1.039	9.09
15	1100.00	3.62±0.02	3.039	17.72	19.34	8.103±0.024	7.817	1.037	9.14
18	1100.00	3.62±0.02	3.039	17.72	19.36	8.103±0.024	7.817	1.037	9.26
21	1100.00	3.64±0.02	3.022	17.72	19.37	8.059±0.025	7.817	1.031	9.31
24	1100.00	3.66±0.02	3.005	17.72	19.38	8.015±0.025	7.817	1.025	9.37
27	1100.00	3.69±0.01	2.891	17.72	19.39	7.947±0.025	7.817	1.017	9.39
30	1100.00	3.70±0.00	2.973	17.72	19.41	7.928±0.026	7.817	1.014	9.54
36	1100.00	3.72±0.01	2.957	17.72	19.43	7.885±0.026	7.817	1.019	9.65
39	1100.00	3.73±0.02	2.949	17.72	19.43	7.864±0.026	7.817	1.006	9.65
42	1100.00	3.80±0.00	2.895	17.72	19.44	7.719±0.028	7.817	0.988	9.71
45	1100.00	3.82±0.04	2.880	17.72	19.44	7.679±0.028	7.817	0.988	9.71
48	1100.00	385 ±0.02	2.857	17.72	19.44	7.619±0.029	7.817	0.988	9.71

Table 3: Resistivity at various levels of water saturation (R_t), water saturation (S_w) and saturation index (I) used for the determination of n for S_2.

Time (Hrs)	**V (volts)**	**I (mA)**	**r_s X10^5 (Ω)**	**Dry weight (g)**	**Wet weight (g)**	**R_t X10^3 (Ωm)**	**R_oX10^3 (Ωm)**	**I**	**S_w (%)**
3	1100.00	3.00±0.02	3.667	16.21	17.46	9.778±0.327	7.980	1.225	7.71
6	1100.00	3.37±0.02	3.264	16.21	17.48	8.704±0.017	7.980	1.091	7.84
9	1100.00	3.38±0.03	3.254	16.21	17.49	8.679±0.017	7.980	1.088	7.90
12	1100.00	3.40±0.00	3.235	16.21	17.50	8.627±0.018	7.980	1.081	7.96
15	1100.00	3.49±0.01	3.152	16.21	17.50	8.405±0.261	7.980	1.053	7.96
18	1100.00	3.52±0.02	3.125	16.21	17.56	8.333±0.258	7.980	1.044	8.33
21	1100.00	3.55±0.01	3.099	16.21	17.61	8.263±0.022	7.980	1.036	8.64
24	1100.00	3.56±0.02	3.080	16.21	17.63	8.240±0.222	7.980	1.033	8.76
27	1100.00	3.57±0.01	3.081	16.21	17.65	8.217±0.023	7.980	1.030	8.88
30	1100.00	3.61±0.01	3.047	16.21	17.71	8.126±0.024	7.980	1.018	9.25
36	1100.00	3.65±0.00	3.014	16.21	17.73	8.037±0.025	7.980	1.007	9.38
39	1100.00	3.68±0.02	2.989	16.21	17.74	7.971±0.025	7.980	0.999	9.44
42	1100.00	3.80±0.00	2.895	16.21	17.76	7.719±0.028	7.980	0.997	9.56
45	1100.00	3.80±0.00	2.895	16.21	17.76	7.719±0.028	7.980	0.967	9.56
48	1100.00	3.80±0.00	2.895	16.21	17.76	7.719±0.028	7.980	0.967	9.56

Table 4: Resistivity at various levels of water saturation (R_t), water saturation (S_w) and saturation index (I) used for the determination of n for S_3

Time (Hrs)	**V (volts)**	**I (mA)**	**r_s X10^5 (Ω)**	**Dry weight (g)**	**Wet weight (g)**	**R_t X10^3 (Ωm)**	**R_o X10^3 (Ωm)**	**I**	**S_w (%)**
3	1100.00	1.08±0.06	10.185	21.16	21.54	27.160±1.714	10.690	2.541	1.80
6	1100.00	1.14±0.06	9.649	21.16	21.78	25.731±1.560	10.690	2.407	2.93
9	1100.00	2.13±0.06	5.164	21.16	21.82	13.771±0.554	10.690	1.288	3.12
12	1100.00	2.24±0.02	4.911	21.16	21.83	13.096±0.512	10.690	1.225	3.17
15	1100.00	2.27±0.04	4.846	21.16	21.84	12.922±0.501	10.690	1.209	3.21
18	1100.00	2.33±0.01	4.721	21.16	21.85	12.589±0.481	10.690	1.178	3.26
21	1100.00	2.41±0.01	4.564	21.16	21.87	12.171±0.456	10.690	1.139	3.36
24	1100.00	2.41±0.02	4.564	21.16	21.93	12.171±0.456	10.690	1.139	3.64
27	1100.00	2.56±0.03	4.297	21.16	21.94	11.459±0.416	10.690	1.072	3.69
30	1100.00	2.80±0.08	3.929	21.16	21.95	10.447±0.363	10.690	0.980	3.73
36	1100.00	2.88±0.03	3.819	21.16	21.96	10.184±0.348	10.690	0.953	3.78
39	1100.00	2.97±0.02	3.704	21.16	21.96	9.877±0.332	10.690	0.924	3.78
42	1100.00	3.02±0.04	3.642	21.16	21.98	9.712±0.323	10.690	0.908	3.88
45	1100.00	3.14±0.18	3.503	21.16	21.98	9.341±0.311	10.690	0.874	3.88
48	1100.00	3.19±0.04	3.488	21.16	21.98	9.301±0.298	10.690	0.861	3.88

Table 5: Resistivity at various levels of water saturation (R_t), water saturation (S_w) and resistivity index (I) used for the determination of n for S_4

Time (Hrs)	**V (volts)**	**I (mA)**	**r_s X10^5 (Ω)**	**Dry weight (g)**	**Wet weight (g)**	**R_t X10^3 (Ωm)**	**R_o X10^3 (Ωm)**	**I**	**S_w (%)**
3	1100.00	2.66±0.02	4.135	22.47	24.68	11.030±0.392	7.674	1.437	9.84
6	1100.00	3.30±0.00	3.056	22.47	24.70	8.148±0.023	7.674	1.062	9.92
9	1100.00	3.63±0.02	3.030	22.47	24.73	8.081±0.024	7.674	1.053	10.06
12	1100.00	3.64±0.02	3.022	22.47	24.74	8.059±0.024	7.674	1.050	10.10
15	1100.00	3.65±0.00	3.014	22.47	24.77	8.037±0.025	7.674	1.047	10.24
18	1100.00	3.68±0.01	2.989	22.47	24.80	7.971±0.025	7.674	1.039	10.37
21	1100.00	3.69±0.01	2.981	22.47	24.84	7.949±0.241	7.674	1.036	10.55
24	1100.00	3.73±0.01	2.949	22.47	24.87	7.864±0.026	7.674	1.025	10.68
27	1100.00	3.75±0.00	2.933	22.47	24.91	7.822±0.027	7.674	1.019	10.86
30	1100.00	3.80±0.00	2.895	22.47	24.93	7.719±0.028	7.674	1.006	10.95
36	1100.00	3.80±0.00	2.895	22.47	24.96	7.719±0.028	7.674	1.006	11.08
39	1100.00	3.86±0.02	2.850	22.47	24.97	7.599±0.029	7.674	0.990	11.13
42	1100.00	3.87±0.01	2.842	22.47	24.98	7.580±0.225	7.674	0.988	11.17
45	1100.00	3.90±0.00	2.821	22.47	24.98	7.521±0.030	7.674	0.980	11.17
48	1100.00	3.92±0.01	2.806	22.47	24.98	7.483±0.030	7.674	0.975	11.17

Table 6: Resistivity at various levels of water saturation (R_t), water saturation (S_w) and resistivity index (I) used for the determination of n for S_5

Time (Hrs)	**V (volts)**	**I (mA)**	**r_s X10^5 (Ω)**	**Dry weight (g)**	**Wet weight (g)**	**R_t X10^3 (Ωm)**	**R_o X10^3 (Ωm)**	**I**	**S_w (%)**
3	1100.00	3.68±0.04	2989	25.23	27.95	8.148±0.023	7.560	1.078	10.78
6	1100.00	3.76±0.01	2.926	25.23	27.95	7.971±0.025	7.560	1.051	10.78
9	1100.00	3.78±0.04	2.910	25.23	27.99	7.801±0.027	7.560	1.032	10.94
12	1100.00	3.79±0.03	2.902	25.23	28.01	7.760±0.232	7.560	1.027	11.02
15	1100.00	3.85±0.02	2.857	25.23	28.03	7.740±0.029	7.560	1.014	11.06
18	1100.00	3.86±0.02	2.850	25.23	28.05	7.619±0.029	7.560	1.008	11.18
21	1100.00	3.86±0.02	2.850	25.23	28.08	7.619±0.029	7.560	1.008	11.30
24	1100.00	3.86±0.02	2.850	25.23	28.10	7.599±0.226	7.560	1.005	11.38
27	1100.00	3.87±0.01	2.842	25.23	28.12	7.599±0.226	7.560	1.005	11.46
30	1100.00	3.87±0.02	2.842	25.23	28.14	7.580±0.029	7.560	1.003	11.53
36	1100.00	3.87±0.02	2.842	25.23	28.17	7.580±0.029	7.560	1.003	11.65
39	1100.00	3.88±0.01	2.835	25.23	28.19	7.560±0.224	7.560	1.000	11.73
42	1100.00	3.88±0.01	2.835	25.23	28.21	7.560±0.224	7.560	1.000	11.81
45	1100.00	3.89±0.01	2.828	25.23	28.21	7.560±0.029	7.560	0.998	11.81
48	1100.00	3.90±0.00	2.821	25.23	28.21	7.560±0.222	7.560	0.995	11.81

Table 7: Resistivity at various levels of water saturation (R_t), water saturation (S_w) and resistivity index (I) used for the determination of n for S_6

Time (Hrs)	**V (volts)**	**I (mA)**	**r_s X10^5 (Ω)**	**Dry weight (g)**	**Wet weight (g)**	**R_t X10^3 (Ωm)**	**R_o X10^3 (Ωm)**	**I**	**S_w (%)**
3	1100.00	3.44±0.02	3.197	19.61	21.54	8.527±0.019	7.824	1.090	9.84
6	1100.00	3.46±0.05	3.179	19.61	21.63	8.478±0.019	7.824	1.084	10.30
9	1100.00	3.47±0.02	3.170	19.61	21.71	8.453±0.263	7.824	1.080	10.71
12	1100.00	3.59±0.01	3.064	19.61	21.72	8.171±0.251	7.824	1.044	10.76
15	1100.00	3.59±0.03	3.064	19.61	21.72	8.171±0.152	7.824	1.044	10.76
18	1100.00	3.60±0.00	3.056	19.61	21.73	8.148±0.023	7.824	1.041	10.81
21	1100.00	3.60±0.00	3.056	19.61	21.74	8.148±0.023	7.824	1.041	10.86
24	1100.00	3.61±0.06	3.047	19.61	21.75	8.126±0.249	7.824	1.039	10.91
27	1100.00	3.65±0.02	3.014	19.61	21.75	8.037±0.025	7.824	1.027	10.91
30	1100.00	3.87±0.02	2.842	19.61	21.78	7.580±0.231	7.824	0.969	11.07
36	1100.00	3.88±0.02	2.835	19.61	21.79	7.560±0.029	7.824	0.966	11.12
39	1100.00	3.88±0.01	2.835	19.61	21.79	7.560±0.029	7.824	0.966	11.12
42	1100.00	3.90±0.00	2.821	19.61	22.10	7.521±0.030	7.824	0.961	12.70
45	1100.00	3.90±0.00	2.821	19.61	22.11	7.521±0.030	7.824	0.961	12.75
48	1100.00	3.90±0.00	2.821	19.61	22.11	7.521±0.030	7.824	0.961	12.75

Table 8: Resistivity at various levels of water saturation (R_t), water saturation (S_w) and resistivity index (I) used for the determination of n for S_7

Time (Hrs)	**V (volts)**	**I (mA)**	**r_s X10^5 (Ω)**	**Dry weight (g)**	**Wet weight (g)**	**R_t X10^3 (Ωm)**	**R_o X10^3 (Ωm)**	**I**	**S_w (%)**
3	1100.00	2.36±0.01	4.661	31.54	32.83	12.430±0.472	8.562	1.452	4.09
6	1100.00	2.53±0.03	4.348	31.54	32.86	11.590±0.421	8.562	1.354	4.19
9	1100.00	2.66±0.05	4.151	31.54	32.89	11.070±0.394	8.562	1.293	4.28
12	1100.00	2.87±0.03	3.056	31.54	32.90	10.220±0.349	8.562	1.194	4.31
15	1100.00	3.03±0.01	3.630	31.54	32.90	9.68±0.322	8.562	1.131	4.31
18	1100.00	3.06±0.02	3.595	31.54	32.92	9.586±0.317	8.562	1.120	4.38
21	1100.00	3.08±0.01	3.571	31.54	32.94	9.524±0.314	8.562	1.112	4.44
24	1100.00	3.08±0.04	3.571	31.54	32.95	9.524±0.314	8.562	1.112	4.47
27	1100.00	3.14±0.02	3.503	31.54	32.96	9.342±0.305	8.562	1.091	4.57
30	1100.00	3.19±0.01	3.448	31.54	32.99	9.195±0.298	8.562	1.074	4.60
36	1100.00	3.22±0.03	3.462	31.54	33.30	9.110±0.294	8.562	1.064	5.58
39	1100.00	3.50±0.04	3.143	31.54	33.39	8.381±0.021	8.562	0.979	5.87
42	1100.00	3.60±0.00	3.056	31.54	33.59	8.148±0.023	8.562	0.952	6.50
45	1100.00	3.73±0.02	2.946	31.54	33.59	7.864±0.026	8.562	0.919	6.50
48	1100.00	3.86±0.02	2.821	31.54	33.59	7.599±0.029	8.562	0.888	6.50

Table 9: Resistivity at various levels of water saturation (R_t), water saturation (S_w) and resistivity index (I) used for the determination of n for S_8

Time (Hrs)	**V (volts)**	**I (mA)**	**r_s X10^5 (Ω)**	**Dry weight (g)**	**Wet weight (g)**	**R_t X10^3 (Ωm)**	**R_o X10^3 (Ωm)**	**I**	**S_w (%)**
3	1100.00	2.80±0.03	3.929	19.84	21.12	10.480±0.363	8.569	1.223	6.45
6	1100.00	3.02±0.02	3.642	19.84	21.18	9±0.324.713	8.569	1.134	6.75
9	1100.00	3.05±0.02	3.607	19.84	21.23	9.618±0.319	8.569	1.122	7.01
12	1100.00	3.10±0.02	3.548	19.84	21.27	9.462±0.310	8.569	1.104	7.21
15	1100.00	3.15±0.01	3.492	19.84	21.33	9.312±0.304	8.569	1.087	7.51
18	1100.00	3.15±0.02	3.492	19.84	21.38	9.312±0.304	8.569	1.087	7.76
21	1100.00	3.16±0.02	3.481	19.84	21.42	9.283±0.302	8.569	1.083	7.96
24	1100.00	3.17±0.05	3.470	19.84	21.49	9.253±0.301	8.569	1.080	8.32
27	1100.00	3.30±0.00	3.303	19.84	21.55	8.809±0.281	8.569	1.028	8.62
30	1100.00	3.39±0.01	3.245	19.84	21.58	8.653±0.017	8.569	1.010	8.77
36	1100.00	3.39±0.01	3.245	19.84	21.63	8.653±0.017	8.569	1.010	9.02
39	1100.00	3.45±0.02	3.188	19.84	21.69	8.502±0.019	8.569	0.992	9.33
42	1100.00	3.56±0.04	3.090	19.84	21.78	8.240±0.023	8.569	0.962	9.78
45	1100.00	3.57±0.02	3.081	19.84	21.78	8.217±0.023	8.569	0.959	9.78
48	1100.00	3.72±0.02	2.957	19.84	21.78	7.885±0.029	8.569	0.920	9.78

Table 10: Resistivity at various levels of water saturation (R_t), water saturation (S_w) and resistivity index (I) used for the determination of n for S_9

Time (Hrs)	**V (volts)**	**I (mA)**	**r_s X10^5 (Ω)**	**Dry weight (g)**	**Wet weight (g)**	**R_t X10^3 (Ωm)**	**R_o X10^3 (Ωm)**	**I**	**S_w (%)**
3	1100.00	3.65±0.00	3.014	29.11	30.65	8.037±0.025	7.485	1.074	5.29
6	1100.00	3.68±0.02	2.989	29.11	30.67	7.971±0.025	7.485	1.065	5.36
9	1100.00	3.74±0.01	2.941	29.11	30.67	7.843±0.022	7.485	1.048	5.36
12	1100.00	3.74±0.02	2.941	29.11	30.69	7.843±0.027	7.485	1.048	5.43
15	1100.00	3.78±0.01	2.910	29.11	30.71	7.760±0.232	7.485	1.037	5.50
18	1100.00	3.84±0.03	2.865	29.11	30.73	7.639±0.028	7.485	1.021	5.57
21	1100.00	3.85±0.02	2.857	29.11	30.74	7.616±0.029	7.485	1.018	5.60
24	1100.00	3.86±0.02	2.850	29.11	30.76	7.599±0.029	7.485	1.015	5.67
27	1100.00	3.86±0.02	2.850	29.11	30.78	7.599±0.030	7.485	1.015	5.74
30	1100.00	3.89±0.03	2.828	29.11	30.79	7.541±0.031	7.485	1.008	5.77
36	1100.00	3.90±0.00	2.821	29.11	30.80	7.521±0.031	7.485	1.005	5.81
39	1100.00	3.90±0.00	2.821	29.11	30.81	7.521±0.031	7.485	1.005	5.84
42	1100.00	3.90±0.01	2.821	29.11	30.82	7.521±0.030	7.485	1.005	5.87
45	1100.00	3.92±0.01	2.806	29.11	30.82	7.483±0.030	7.485	1.000	5.87
48	1100.00	3.98±0.01	2.764	29.11	30.82	7.370±0.031	7.485	0.985	5.87

Table 11: Resistivity at various levels of water saturation (R_t), water saturation (S_w) and resistivity index (I) used for the determination of n for S_{10}

Time (Hrs)	**V (volts)**	**I (mA)**	**r_s X10^5 (Ω)**	**Dry weight (g)**	**Wet weight (g)**	**R_t X10^3 (Ωm)**	**R_o X10^3 (Ωm)**	**I**	**S_w (%)**
3	1100.00	3.50±0.00	3.143	13.36	14.85	8.381±0.021	8.160	1.027	11.15
6	1100.00	3.50±0.00	3.143	13.36	14.86	8.381±0.021	8.160	1.027	11.23
9	1100.00	3.52±0.01	3.125	13.36	14.86	8.333±0.258	8.160	1.021	11.23
12	1100.00	3.56±0.02	3.080	13.36	14.87	8.240±0.022	8.160	1.010	11.30
15	1100.00	3.57±0.02	3.081	13.36	14.88	8.217±0.023	8.160	1.007	11.38
18	1100.00	3.58±0.01	3.073	13.36	14.88	8.194±0.023	8.160	1.004	11.38
21	1100.00	3.58±0.01	3.073	13.36	14.89	8.194±0.023	8.160	1.004	11.45
24	1100.00	3.59±0.01	3.064	13.36	14.90	8.171±0.025	8.160	1.001	11.43
27	1100.00	3.59±0.01	3.064	13.36	14.90	8.171±0.025	8.160	1.001	11.60
30	1100.00	3.60±0.00	3.056	13.36	14.91	8.148±0.023	8.160	0.999	11.68
36	1100.00	3.60±0.00	3.056	13.36	14.92	8.148±0.023	8.160	0.999	11.68
39	1100.00	3.60±0.00	3.056	13.36	14.92	8.148±0.023	8.160	0.999	11.68
42	1100.00	3.60±0.00	3.056	13.36	14.92	8.148±0.023	8.160	0.999	11.68
45	1100.00	3.60±0.00	3.056	13.36	14.92	8.148±0.023	8.160	0.999	11.68
48	1100.00	3.60±0.00	3.056	13.36	14.92	8.148±0.023	8.160	0.999	11.68

Table 12: Resistivity at various levels of water saturation (R_t), water saturation (S_w) and resistivity index (I) used for the determination of n for S_{11}

Time (Hrs)	**V (volts)**	**I (mA)**	**r_s X10^5 (Ω)**	**Dry weight (g)**	**Wet weight (g)**	**R_t X10^3 (Ωm)**	**R_o X10^3 (Ωm)**	**I**	**S_w (%)**
3	1100.00	3.22±0.01	3.462	22.96	24.70	9.110±0.294	8.050	1.132	7.58
6	1100.00	3.32±0.04	3.313	22.96	24.70	8.835±0.015	8.050	1.098	7.58
9	1100.00	3.34±0.02	3.293	22.96	24.73	8.782±0.016	8.050	1.091	7.71
12	1100.00	3.41±0.01	3.226	22.96	24.75	8.602±0.018	8.050	1.069	7.80
15	1100.00	3.42±0.01	3.216	22.96	24.78	8.577±0.018	8.050	1.066	7.93
18	1100.00	3.42±0.02	3.216	22.96	24.78	8.577±0.018	8.050	1.066	7.93
21	1100.00	3.49±0.01	3.152	22.96	24.85	8.405±0.020	8.050	1.044	8.23
24	1100.00	3.50±0.00	3.143	22.96	24.90	8.381±0.021	8.050	1.041	8.45
27	1100.00	3.50±0.00	3.143	22.96	24.96	8.381±0.021	8.050	1.041	8.71
30	1100.00	3.64±0.01	3.022	22.96	24.98	8.059±0.024	8.050	1.001	8.79
36	1100.00	3.77±0.01	2.918	22.96	24.98	7.781±0.027	8.050	0.967	8.79
39	1100.00	3.78±0.01	2.910	22.96	25.02	7.760±0.232	8.050	0.964	8.97
42	1100.00	3.78±0.02	2.910	22.96	25.04	7.760±0.232	8.050	0.964	9.06
45	1100.00	3.79±0.01	2.902	22.96	25.04	7.740±0.029	8.050	0.962	9.06
48	1100.00	3.80±0.02	2.895	22.96	25.04	7.719±0.028	8.050	0.959	9.06

Table 13: Resistivity at various levels of water saturation (R_t), water saturation (S_w) and resistivity index (I) used for the determination of n for S_{12}

Time (Hrs)	**V (volts)**	**I (mA)**	**r_s X10^5 (Ω)**	**Dry weight (g)**	**Wet weight (g)**	**R_t X10^3 (Ωm)**	**R_o X10^3 (Ωm)**	**I**	**S_w (%)**
3	1100.00	3.52±0.04	3.125	22.36	23.92	8.333±0.021	7.975	1.045	6.98
6	1100.00	3.56±0.01	3.090	22.36	23.92	8.240±0.022	7.975	1.033	6.98
9	1100.00	3.58±0.01	3.073	22.36	23.94	8.194±0.023	7.975	1.028	7.07
12	1100.00	3.58±0.01	3.073	22.36	23.96	8.194±0.023	7.975	1.028	7.16
15	1100.00	3.59±0.01	3.064	22.36	23.98	8.171±0.251	7.975	1.025	7.25
18	1100.00	3.59±0.01	3.064	22.36	24.00	8.171±0.251	7.975	1.025	7.34
21	1100.00	3.60±0.00	3.056	22.36	24.01	8.148±0.023	7.975	1.022	7.38
24	1100.00	3.60±0.00	3.056	22.36	24.02	8.148±0.023	7.975	1.022	7.42
27	1100.00	3.63±0.01	3.030	22.36	24.02	8.081±0.024	7.975	1.013	7.42
30	1100.00	3.65±0.00	3.014	22.36	24.03	8.037±0.025	7.975	1.008	7.47
36	1100.00	3.67±0.01	2.997	22.36	24.05	7.993±0.025	7.975	1.002	7.56
39	1100.00	3.69±0.03	2.981	22.36	24.07	7.949±0.025	7.975	0.997	7.65
42	1100.00	3.74±0.01	2.941	22.36	24.09	7.843±0.026	7.975	0.984	7.74
45	1100.00	3.75±0.03	2.933	22.36	24.09	7.822±0.027	7.975	0.981	7.74
48	1100.00	3.76±0.01	2.926	22.36	24.09	7.801±0.027	7.975	0.978	7.74

Table 14: Resistivity at various levels of water saturation (R_t), water saturation (S_w) and resistivity index (I) used for the determination of n for S_{13}

Time (Hrs)	**V (volts)**	**I (mA)**	**r_s X10^5 (Ω)**	**Dry weight (g)**	**Wet weight (g)**	**R_t X10^3 (Ωm)**	**R_o X10^3 (Ωm)**	**I**	**S_w (%)**
3	1100.00	2.63±0.01	4.183	19.60	20.22	11.150±0.399	8.118	1.374	3.16
6	1100.00	2.75±0.04	4.000	19.60	20.24	10.670±0.373	8.118	1.314	3.27
9	1100.00	2.92±0.03	3.767	19.60	20.25	10.050±0.340	8.118	1.238	3.32
12	1100.00	3.01±0.04	3.655	19.60	20.28	9.745±0.325	8.118	1.200	3.47
15	1100.00	3.13±0.04	3.514	19.60	20.30	9.372±0.307	8.118	1.155	3.57
18	1100.00	3.20±0.00	3.438	19.60	20.31	9.167±0.297	8.118	1.129	3.62
21	1100.00	3.42±0.01	3.216	19.60	20.32	8.557±0.018	8.118	1.057	3.67
24	1100.00	3.46±0.03	3.179	19.60	20.34	8.478±0.020	8.118	1.044	3.78
27	1100.00	3.55±0.02	3.099	19.60	20.35	8.263±0.022	8.118	1.018	3.83
30	1100.00	3.60±0.02	3.056	19.60	20.35	8.148±0.023	8.118	1.004	3.83
36	1100.00	3.63±0.02	3.030	19.60	20.37	8.081±0.024	8.118	0.995	3.93
39	1100.00	3.66±0.02	3.006	19.60	20.39	8.015±0.025	8.118	0.987	4.03
42	1100.00	3.66±0.02	3.006	19.60	20.41	8.015±0.025	8.118	0.987	4.13
45	1100.00	3.82±0.02	2.880	19.60	20.41	7.679±0.028	8.118	0.946	4.13
48	1100.00	3.83±0.01	2.872	19.60	20.41	7.659±0.028	8.118	0.944	4.13

Table 15: Resistivity at various levels of water saturation (R_t), water saturation (S_w) and resistivity index (I) used for the determination of n for S_{14}

Time (Hrs)	**V (volts)**	**I (mA)**	**r_s X10^5 (Ω)**	**Dry weight (g)**	**Wet weight (g)**	**R_t X10^3 (Ωm)**	**R_o X10^3 (Ωm)**	**I**	**S_w (%)**
3	1100.00	3.48±0.01	3.161	13.33	15.02	8.426±0.261	7.774	1.084	12.68
6	1100.00	30.02	3.107	13.33	15.05	8.286±0.022	7.774	1.066	12.90
9	1100.00	3.56±0.02	3.090	13.33	15.10	8.240±0.022	7.774	1.060	13.28
12	1100.00	3.60±0.00	3.056	13.33	15.10	8.148±0.023	7.774	1.048	13.28
15	1100.00	3.64±0.02	3.022	13.33	15.10	8.050±0.024	7.774	1.037	13.65
18	1100.00	3.68±0.04	2.989	13.33	15.15	7.971±0.025	7.774	1.025	14.03
21	1100.00	3.69±0.01	2.981	13.33	15.22	7.949±0.025	7.774	1.023	14.18
24	1100.00	3.70±0.00	2.973	13.33	15.24	7.928±0.026	7.774	1.020	14.33
27	1100.00	3.73±0.00	2.949	13.33	15.27	7.864±0.026	7.774	1.012	14.55
30	1100.00	3.75±0.02	2.933	13.33	15.29	7.822±0.027	7.774	1.006	14.70
36	1100.00	3.77±0.03	2.918	13.33	15.30	7.781±0.027	7.774	1.001	14.78
39	1100.00	3.78±0.01	2.910	13.33	15.31	7.760±0.232	7.774	0.988	14.85
42	1100.00	3.82±0.02	2.880	13.33	15.34	7.679±0.028	7.774	0.988	15.08
45	1100.00	3.83±0.01	2.872	13.33	15.34	7.659±0.028	7.774	0.985	15.08
48	1100.00	3.85±0.02	2.857	13.33	15.34	7.619±0.029	7.774	0.980	15.08

n=0.70

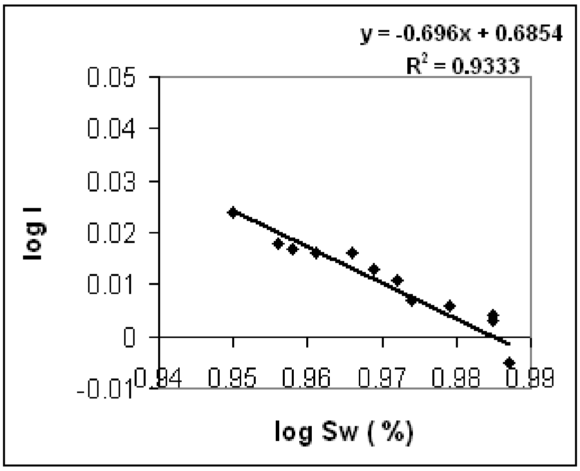

Fig. 2: Determination of *n* for S_1

n=0.50

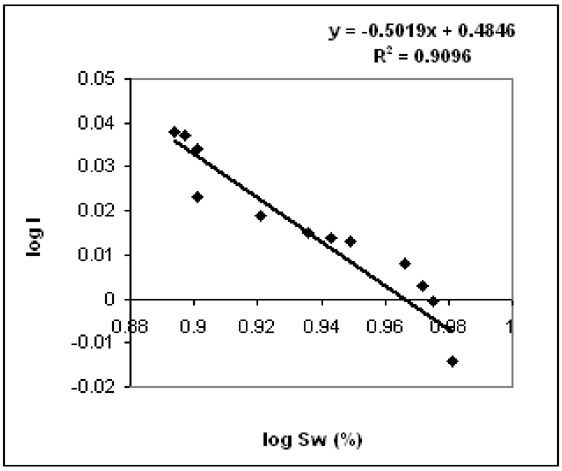

Fig. 3: Determination of *n* for S_2

n=1.56

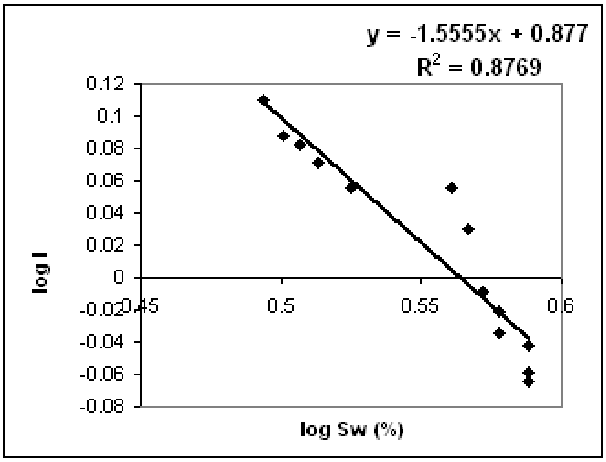

Figure 4: Determination of *n* for S_3

n=0.63

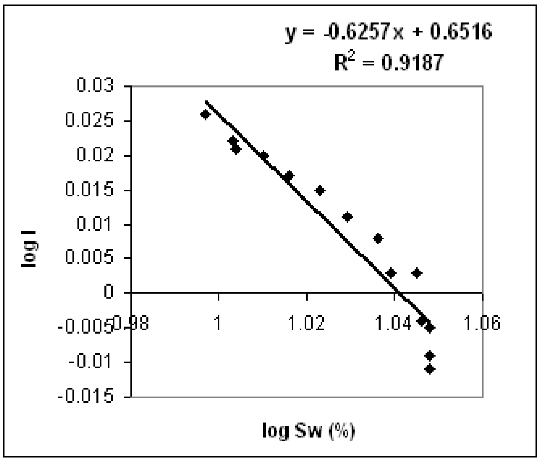

Figure 5: Determination of *n* for S_4

n=0.55

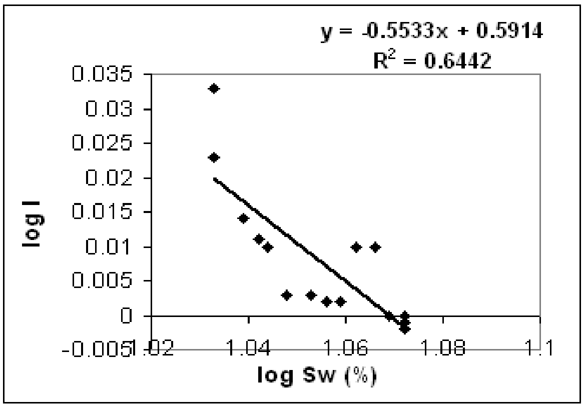

Figure 6: Determination of *n* for S_5

n=0.51

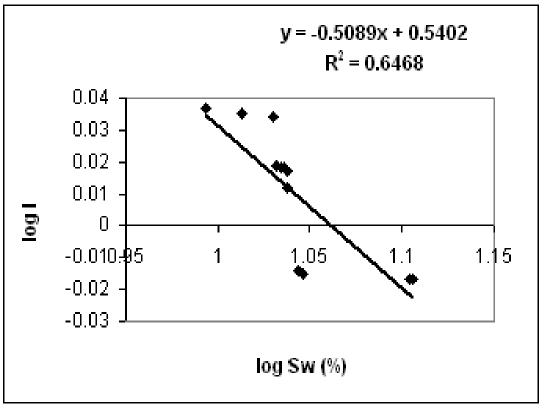

Figure 7: Determination of *n* for S_6

n=0.65

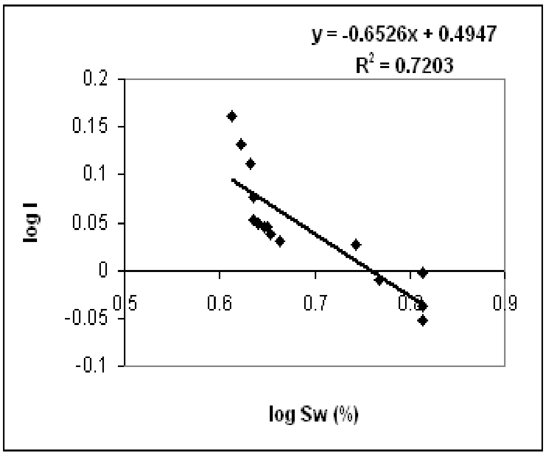

Figure 8: Determination of *n* for S_7

n=0.52

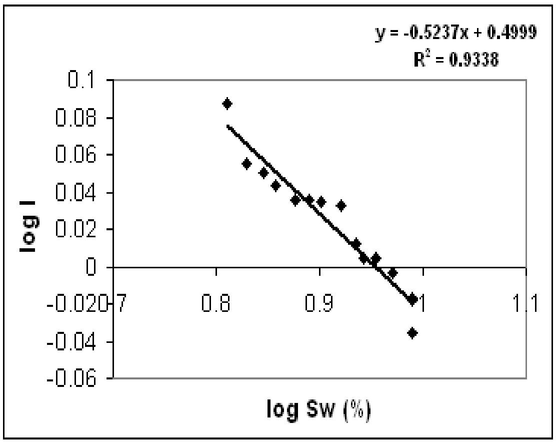

Figure 9: Determination of *n* for S_8

n=0.64

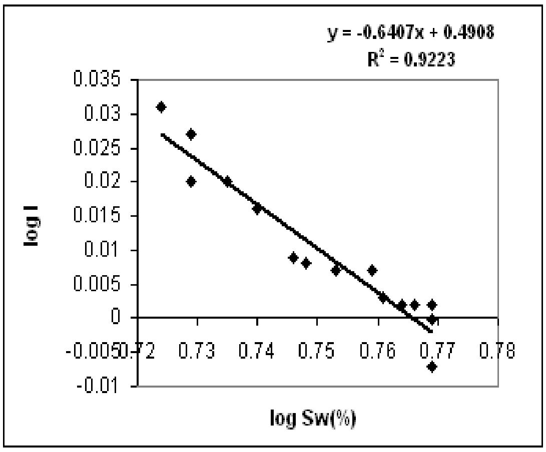

Figure 10: Determination of *n* for S_9

n=0.58

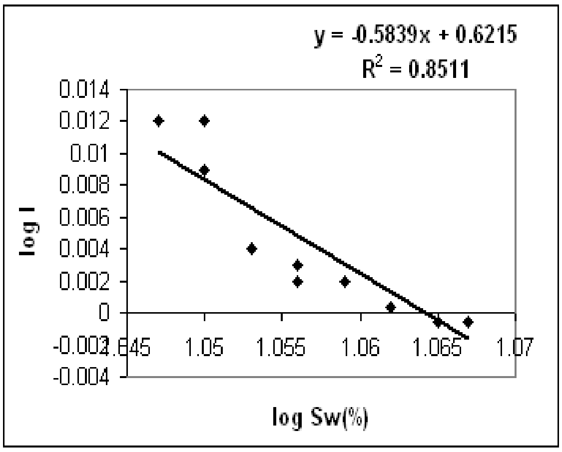

Figure 11: Determination of *n* for S_{10}

n=0.77

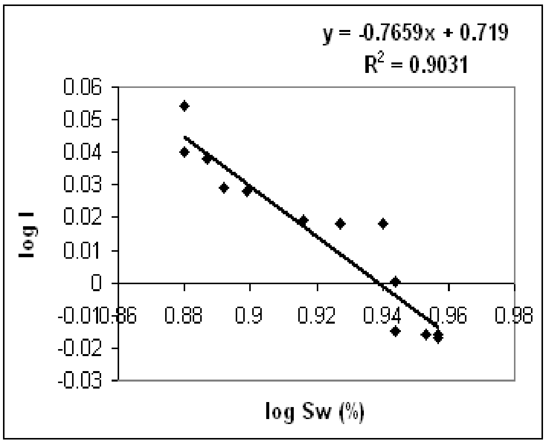

Figure 12: Determination of *n* for S_{11}

n=0.52

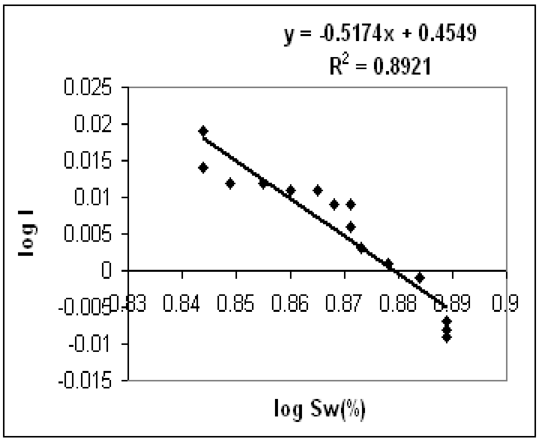

Figure 13: Determination of *n* for S_{12}

n=1.38

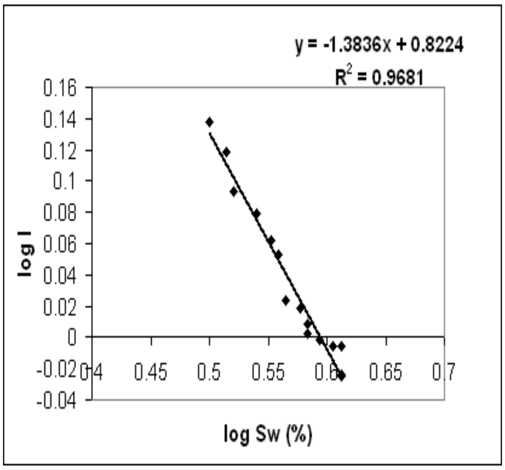

Figure 14: Determination of n for S_{13}

n=0.51

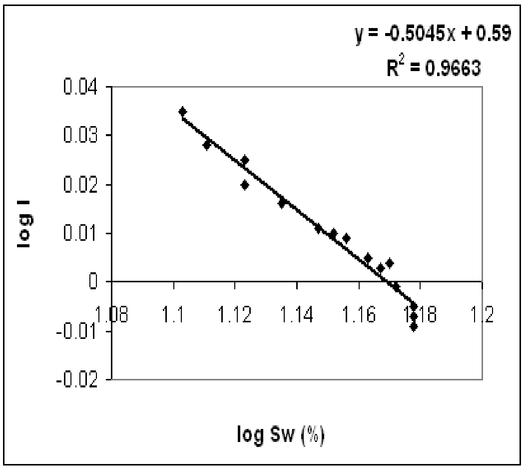

Figure 15: Determination of n for S_{14}

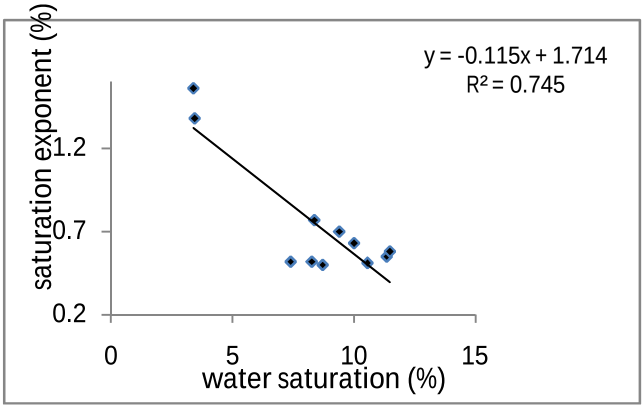

Figure 16:Rrelationship between water saturation and saturation exponent.

CONCLUSION

Generally, saturation exponent varies with S_W depending on rock texture and porosity (Diederix, 1982, Swason, 1985, Schon, 1996). Worthington *et al* (1992) showed that n is constant for unimodal pore distribution and increases with water saturation for rocks with microporosity**.**

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