RGSA – Revista de Gestão Social e Ambiental
ISSN: 1981-982X
Submission date: 01/29/2023
Acceptance date: 03/27/2024
DOI: https://doi.org/10.24857/rgsa.v18n9-062
Organization: Interinstitutional Scientific Committee
Chief Editor: Christian Luiz da Silva
Assessment: Double Blind Review pelo SEER/OJS

HOW DO POROSITY, SIZE AND INTERCONNECTIVITY OF PORES INFLUENCE THE VALUES OF THE ARCHIE EQUATION EXPONENTS IN CARBONATE AND SANDY ROCKS?

Juliana Targino Batista[1]
José Agnelo Soares[2]
Anne Beatrice Guedes Sobrino [3]
Nathália Amorim Lima de Moraes[4]

ABSTRACT

Objective: The aim of this study is to investigate the exponents of the Archie equation in order to support the evaluation of hydrocarbon or groundwater reserves through electrical resistivity measurements of subsurface rocks.

Theoretical Framework: The Archie equation describes the relationship between the electrical resistivity of a rock and its water saturation and depends on the cementation (m) and saturation (n) exponents. Several authors state that electrical resistivity and the exponents m and n depend on the size, geometry, and connectivity of the pores.

Method: This article applies the finite element method to simulate the propagation of the electric field in digital rock models and thus evaluate the Archie exponents.

Results and Discussion: Our results indicate that the relationship between these exponents and pore attributes is different for values below or above a threshold. The variables with the greatest influence on m are the porosity of macropores and their interconnectivity, as well as the volumetric fraction of the microporous phase. As for the saturation exponent, the variables with the greatest influence are the porosity of macropores and the interconnectivity of both potentially conductive domains.

Research Implications: The practical and theoretical implications of this research are discussed, providing insights into how the results can be applied or influence practices in the field of underground natural resource assessment. These implications may cover the sectors of hydrocarbon production, groundwater, geo-environmental investigations, and geotechnical studies.

Originality/Value: This study contributes to the literature by presenting an innovative method for determining the exponents of the Archie equation. The relevance and value of this research are evidenced by its high economic impact on the aforementioned sectors and by its applicability anywhere.

Keywords: Sedimentary Rock, Formation Evaluation, Hydrocarbons, Petrophysics, Digital Rock Model.

---

[1] Universidade Federal de Campina Grande, Paraíba, Brazil. E-mail: juliana-targino@hotmail.com
Orcid: https://orcid.org/0009-0008-3342-798X
[2] Universidade Federal de Campina Grande, Paraíba, Brazil. E-mail: jose.agnelo@professor.ufcg.edu.br
Orcid: https://orcid.org/0000-0001-6956-4013
[3] Universidade Federal de Campina Grande, Paraíba, Brazil. E-mail: amorimnathalia.18@gmail.com
Orcid: https://orcid.org/0009-0005-7284-9622
[4] Universidade Federal de Campina Grande, Paraíba, Brazil. E-mail: annebeatriceguedes@hotmail.com
Orcid: https://orcid.org/0009-0008-2193-8483

COMO A POROSIDADE, O TAMANHO E A INTERCONECTIVIDADE DOS POROS INFLUENCIAM NOS VALORES DOS EXPOENTES DA EQUAÇÃO DE ARCHIE EM ROCHAS CARBONÁTICAS E ARENOSAS?

RESUMO

Objetivo: O objetivo deste estudo é investigar os expoentes da equação de Archie, com o intuito de da suporte à avaliação de reservas de hidrocarbonetos ou de água subterrânea através de medições de resistividade elétrica das rochas de subsuperfície

Referencial Teórico: A equação de Archie descreve a relação entre a resistividade elétrica de uma rocha e sua saturação em água e depende dos expoentes de cimentação (m) e de saturação (n). Diversos autores afirmam que a resistividade elétrica e os expoentes m e n dependem do tamanho, da geometria e da conectividade dos poros.

Método: Este artigo aplica o método dos elementos finitos para simular a propagação do campo elétrico em modelos digitais de rocha e assim avaliar os expoentes de Archie.

Resultados e Discussão: Nossos resultados indicam que a relação entre esses expoentes e os atributos dos poros é diferente para valores abaixo ou acima de um patamar. As variáveis de maior influência sobre m são a porosidade dos macroporos e sua interconectividade, além de fração volumétrica da fase microporosa. Quanto ao expoente de saturação as variáveis de maior influência são a porosidade dos macroporos e a interconectividade de ambos os domínios potencialmente condutivos.

Implicações da Pesquisa: As implicações práticas e teóricas desta pesquisa são discutidas, fornecendo insights sobre como os resultados podem ser aplicados ou influenciar práticas no campo de avaliação de recursos naturais subterrâneos. Essas implicações podem abranger os setores de produção de hidrocarbonetos, de água subterrânea, investigações geoambientais e de estudos geotécnicos.

Originalidade/Valor: Este estudo contribui para a literatura ao apresentar um método inovador para a determinação dos expoentes da equação de Archie. A relevância e o valor desta pesquisa são evidenciados pelo elevado impacto econômicos aos setores supracitados e por se constituir em um método aplicável em qualquer lugar.

Palavras-chave: Rocha sedimentar, Avaliação de Formações, Hidrocarbonetos, Petrofísica, Modelo digital de rocha.

¿COMO A POROSIDADE, O TAMANHO E A INTERCONECTIVIDADE DOS POROS INFLUENCIAM NOS VALORES DOS EXPOENTES DA EQUAÇÃO DE ARCHIE EM ROCHAS CARBONÁTICAS E ARENOSAS?

RESUMEN

Objetivo: El propósito de este estudio es investigar los exponentes de la ecuación de Archie con el fin de apoyar la evaluación de reservas de hidrocarburos o agua subterránea mediante mediciones de resistividad eléctrica de las rocas subsuperficiales.

Marco Teórico: La ecuación de Archie describe la relación entre la resistividad eléctrica de una roca y su saturación en agua y depende de los exponentes de cementación (m) y de saturación (n). Varios autores afirman que la resistividad eléctrica y los exponentes m y n dependen del tamaño, la geometría y la conectividad de los poros.

Método: Este artículo aplica el método de los elementos finitos para simular la propagación del campo eléctrico en modelos digitales de roca y así evaluar los exponentes de Archie.

Resultados y Discusión: Nuestros resultados indican que la relación entre estos exponentes y los atributos de los poros es diferente para valores por debajo o por encima de un umbral. Las variables con mayor influencia en m son la porosidad de los macroporos y su interconectividad, así como la fracción volumétrica de la fase microporosa. En cuanto al exponente de saturación, las variables con mayor influencia son la porosidad de los macroporos y la interconectividad de ambos dominios potencialmente conductivos.

Implicaciones de la investigación: Se discuten las implicaciones prácticas y teóricas de esta investigación, proporcionando ideas sobre cómo los resultados pueden aplicarse o influir en prácticas en el campo de la evaluación de recursos naturales subterráneos. Estas implicaciones pueden abarcar los sectores de producción de hidrocarburos, agua subterránea, investigaciones geoambientales y estudios geotécnicos.

Originalidad/Valor: Este estudio contribuye a la literatura al presentar un método innovador para determinar los exponentes de la ecuación de Archie. La relevancia y el valor de esta investigación se evidencian por su alto impacto económico en los sectores mencionados anteriormente y por su aplicabilidad en cualquier lugar.

Palabras clave: Roca sedimentaria, Evaluación de formaciones, Hidrocarburos, Petrofísica, Modelo Digital de Roca.

1 INTRODUCTION

Archie (1942) published the most important paper to date for the quantitative interpretation of well geophysical profiles, especially for the evaluation of hydrocarbon reserves (Sen, 1997; Hamada, 2010; Gholanlo, Yeganeh & Dehrizi, 2018; Soleymanzadeh, Kaj, Kord & Monjezi, 2021). In that classic article, the author presents two equations. The first defines the so-called Formation Factor, which relates the resistivity of a fully saturated rock to the resistivity of the brine that saturates it, as well as a relationship between the Formation Factor and the porosity of the rock - establishing the exponent m as the inclination of the curve between these properties. The second equation establishes the relationship between the Formation Factor and the fluid saturation, with the introduction of the exponent n as its proportionality factor. Later, in 1952, Winsauer, Shearin, Masson & Williams proposed a modification to Archie's model by introducing a so-called tortuosity coefficient (a).

The precise determination of the exponents of Archie's equation, for each specific lithological type, is currently a challenge; it involves very lengthy laboratory tests or inaccurate analysis of well profiling data. This paper presents a new method for determining the exponents of Archie's equation by numerical simulation on digital rock models generated from x-ray microtomographic images.

2 THEORETICAL FRAME

The best-known form of Archie's equation is given by (Olsen, Hongdul & Fabricius 2008; Hamada, 2010; Sharifi, Saadat, Kazemzadeh & Mahmoudian, 2012; Xiao, Mao, Li & Jin (2013); Adebayo, Al-Yousef & Mahmoud, 2015; Dashtian, Yang & Sahimi, 2015):

$$S_w{}^n = \frac{a\,R_w}{\emptyset^m R_t} \qquad (1)\ (2)$$

Where:

Sw is the water saturation
Rw is the resistivity of the water that saturates the rock
∅ is the porosity of the rock
Rt is the resistivity of rock containing hydrocarbons

The coefficient a and the exponents m and n are the parameters of the Archie equation. m is known as the cementation exponent and n as the saturation exponent. Glover (2009; 2016) showed that there is no theoretical justification for the tortuosity factor of the Archie equation, indicating that its existence is justified only as a way to compensate for errors concerning the measurement of the porosity of the rock, and the salinity and temperature of the fluid. This article adopts the concept proposed by Glover (2009; 2016) in which a is considered equal to unity.

The values of the cementing exponent m and the saturation exponent n are sources of uncertainty in the calculation of fluid saturation in heterogeneous carbonaceous reservoirs (Mardi, Nurozi & Edalatkhah, 2012). Olsen *et al.*, (2008); Glover, (2010) state that for limestones and sandstones there is a relationship between the cementing exponent and the specific surface, which consists of a measure of the size of grains or pores. For Glover (2009) higher m values are associated with lower pore connectivity. According to the author, most porous sandy sediments have cementation exponents between 1.5 and 2.5, and values higher than 2.5 and up to 5 are generally found in carbonates where the pores are less interconnected.

Dashtian *et al.* (2015) also state that m increases as the interconnectivity of pores decreases, and indicates that the presence of clay minerals leads to a smaller and unreal estimate of the value of the cementation exponent. Liu, Zhao, Luo, Chen & He (2015) associate the values of Archie's m and n parameters with the efficiency in conducting electric current through the conductive fluid saturated pore system. For those authors, the more the pores are well interconnected the greater will be the electrical efficiency of the rock and the smaller will be the value of n.

For some authors the resistivity of the rock, and consequently the value of the saturation exponent, depends on the type, quantity and connectivity of pores. Sen (1997) states that in microporous carbonates n decreases with increasing microporosity. Cerepi (2004) points out that electrical conductivity does not depend only on porosity, but is also strongly sensitive to the microstructure of the porous system, the connectivity of the porous space and its microgeometry. In carbonaceous rocks micropores provide connectivity and fluid path between otherwise disconnected larger pore scales (Yao, Wang, Yang, Hu & Wang 2013; Harland, Wood, Curtis, Van Dijke, Stratford, Jiang, Kallel & Sorbie 2015). According to Harland *et al.* (2015) the topology (connectivity) of the pore network can be described by calculating the Euler number.

In this work the exponents of Archie's equation are determined for fourteen digital rock samples, ten carbonaceous and four sandy. These parameters are calculated by topological analysis of the digital rock models and numerical simulation, by finite element method, by propagating an electric field to two fluid saturation scenarios: 1) fully water-saturated macropores, and 2) fully oil-saturated macropores. In either scenario the micropores will always be saturated with water. The digital rock models were obtained by x-ray microtomography.

3 METHODOLOGY

Fourteen rock samples of geological formations coming from various sedimentary basins were analyzed. Table 1 identifies all rock samples used in this survey.

Table 1

Identification of rock samples analyzed in this survey.

Sample Code	Lithology	Training	Geographic Location	Age
CY12	Limestone	Edwards Plateau	Austin Chalk (USA)	Cretaceous
PC1A		Riachuelo	Carapeba Quarry	
CR2		Jandaíra	Waterfall Roncador	
ROSARY			Lajedo Rosário	
AROBL			Lajedo Arapuá	
IL3		Bedford	Indiana (USA)	Mississippian
CALRONC	Calcrete	Jandaíra	Waterfall Roncador	Cretaceous
SD12	Dolomite	Thornton	Silurian Dolomite (USA)	Silurian
PC3C		Riachuelo	Carapeba Quarry	Cretaceous

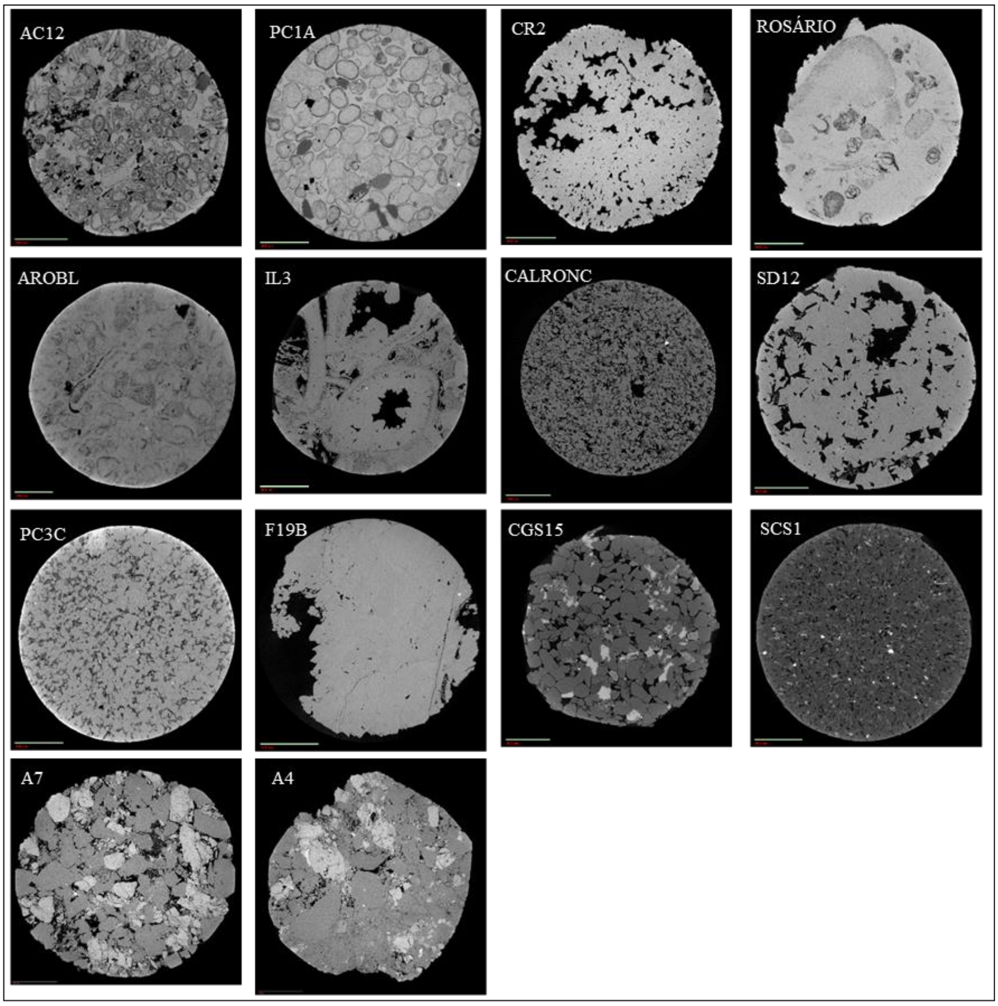
F19B	Coquina	Morro do Chaves	The Alagoas basin	
CGS15	Sandstone	Green Table	Colorado (US)	
SCS1		Ohio	Ohio (US)	Mississippian
A7		Antenor Navarro	The Fish River Basin	Cretaceous
A4				

The analyzed lithotypes are comprised of fine sandstone (CGS15) to thick sandstones (A7 and A4), as well as limestones, calcrete (secondary crusts of calcium carbonate), dolomites (predominance of Mg in its composition) and coquine (sedimentary rock formed by the accumulation of shells). Figure 1 presents microtomographic images of the fourteen samples analyzed.

From the digital images of each rock sample, a data cube with 100^3 pixels was extracted from its center. These data cubes were used for all subsequent analyzes. The pixel size of the images ranges from 1.4 to 2.65 µm. Each data cube was segmented into three domains: 1) macropores; 2) microporous phase; and 3) mineral matrix.

Figure 1

Microtomographic images recorded in the rock samples analyzed.



Next, an analysis of the connectivity (topology) of the potentially conductive domains was carried out. The mineral matrix is considered to be infinitely resistive in all simulated saturation scenarios, so topological research has only been performed for the macropore and micropore domains, which may contain conductive fluids. It is adopted in this work as a connectivity index (IC) determined from the Euler number, which is obtained in the analysis of the digital rock model, for each potentially conductive domain. The Euler number is a large negative number when the domain is strongly interconnected, and is a large positive number when the domain has low interconnectivity. In order to obtain an index that presents a direct relationship with connectivity, and whose values vary in scale from zero to one, in this work the connectivity indicator index was defined as:

$$\mathrm{ICP} = 0.5 - \frac{(0.5 * \mathrm{NEP})}{|\mathrm{NEP}_{\mathrm{min}}|} \quad (1)$$

Where:

PCI is the connectivity index of macropores

NEP is the Euler number of macropores

NEPmin is the minimum NEP value of all analyzed samples.

Likewise, for the microporous domain, its connectivity index is defined as:

$$\mathrm{CFI} = 0.5 - \frac{(0.5 * \mathrm{NE}FI)}{|\mathrm{NE}FI_{\mathrm{min}}|} \qquad (3)$$

Where:

ICFI is the microporous domain connectivity index

NEFI is your Euler number

NEFImin is the minimum NEFI value for all samples analyzed.

Three-dimensional meshes of tetragonal elements, representative of the digital models of the rock samples, were generated. Each mesh contains the volume, shape and topology properties of the three domains and is intended for numerical simulation of electrical properties under different fluid saturation scenarios. Avizo Fire® software was used for the initial processing of digital images as well as for topological analysis. ScanIP® software was used to generate the meshes. The Comsol Multiphysics® software was applied to the numerical simulation of electrical properties using the finite element technique.

For the numerical simulation, two scenarios of fluid saturation were adopted: 1) The rock is 100% saturated with water, that is, the macropores and the intermediate phase are conductive; 2) The rock contains oil in the macropores, which are therefore resistive and the micropores contained in the intermediate phase, because they always contain water, are conductive.

In numerical simulations, a 12 volt electric potential difference was applied between the lower and upper edges of each numerical mesh. The result provides the spatial distribution of the electric potential and the current density (J) for each saturation scenario investigated. For the numerical simulations, the electrical properties indicated in Table 2 were adopted for each material.

Table 2

Electrical properties adopted in numerical simulations.

Property	**Water**	**Oil**	**Clay or micrite**	**Limestone, Calcrete or Coke**	**Dolomite**	**Sandstone**
Electrical resistivity (ohm.m)	0.2	1e+04	20	2.1e+05	9e+02	2.1e+05
Relative Permissiveness	81	20	36	7.3	8.3	7.3

Since the value of the cementing exponent m is not affected by the fluid saturation change, the value of m of a given rock sample is the same for both fluid saturation scenarios analyzed. Since the Formation Factor (F) can be estimated by equations 4 and 5, manipulating them gives expression 6 for the calculation of the cementation exponent.

$$F = \frac{a}{\emptyset^{m}} \qquad (4)$$

Where:

is the porosity measured directly from the ratio of the volumes of the porous domains of the mesh to those of the domains marked as mineral matrix.

$$F = \frac{R_O}{R_w} \qquad (5)$$

Where:

> Ro is the resistivity of the rock 100% saturated with water, value extracted from the simulation for the first scenario of fluid saturation

Rw is the resistivity of the water that saturates the rock, according to the value presented in Table 2.

$$m = \frac{\ln(a) - \ln(F)}{\ln(\emptyset)} \qquad (6)$$

The value of the saturation exponent *n* is directly affected by fluid saturation, so its value is calculated for a saturation scenario in which the saturation in water is less than 100%.

Considering the general case in which a rock finds itself at water saturation S_w and exhibits resistivity R_t, the saturation exponent can be calculated by equation 7.

Numerical simulation gives the value of the current density J, so the resistivity of the rock for each fluid saturation scenario is given by equation 8.

$$R_t = \frac{T}{J \cdot L} \qquad (8)$$

Where:

T is the applied voltage (in this case 12 volts)
J is the current density
L is the length of the rock sample.

In order to identify consistent relationships between the parameters of Archie's equation, determined from the numerically simulated electrical properties, and other properties represented in the digital rock models, statistical analyzes were applied to the data. Statistical analysis has shown that consistent relationships can be obtained through the piecewise linear regression technique. This type of regression provides two linear equations, one for values of the dependent variable above a given breakpoint, and another for values below that breakpoint. Knowing the value of the dependent variable, one can define which of the two linear equations should be considered. However, assuming that the value of the dependent variable is unknown, if the independent variables are all in the same range (0 to 1, for example, as is the case with the data in this article) then the

4 RESULTS AND DISCUSSIONS

Figure 2 presents the digital models of the investigated samples, which are represented by their numerical meshes with the three domains and their respective properties, as presented in Table 2. In this figure the colors indicate the various domains: blue → pores, green → microporous phase and red → mineral matrix.

Macropores are formed mainly by intergranular spaces and their contours can be clearly identified in microtomographic images. The microporous domain in the carbonaceous samples corresponds to the mycritic matrix and in the sandy samples corresponds to the clay minerals.

The microporous phase is essentially continuous, representing the space in which much of the irremovable water is found.

Figure 3 presents the result of the simulation of electric field propagation in the digital model of each sample of rock saturated with water.

Figure 4 presents the result of the quantification of the volumetric fractions of the macropores and the microporous phase in the digital rock models (MDRs). It is noted that the microporous phase is dominant in the sandy samples (CGS15, SCS1, A7 and A4), unlike the carbonaceous samples (except for the AC12 sample which is quite microporous). This is because the sandy samples tend to have a greater share of clay minerals in their composition compared with the carbonaceous samples.

Figure 2

Digital rock models identifying the three domains: mineral matrix (red), macropores (blue) and microporous phase (green).

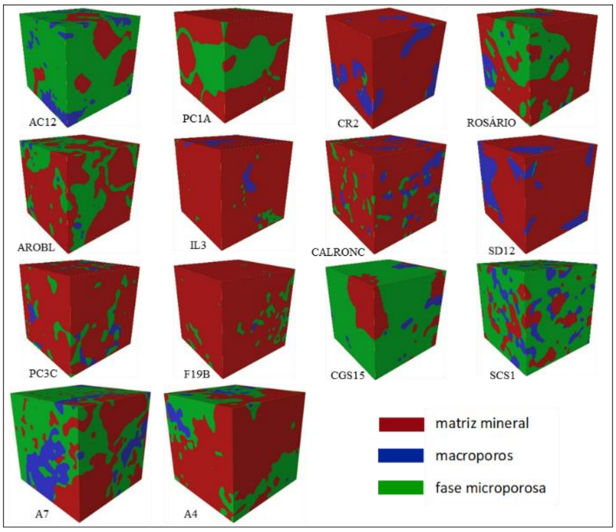


Figure 5 indicates the connectivity of the potentially conductive domains of all samples through the connectivity indexes, as defined by equations 2 and 3. The values of these indices range from zero to one, with the closer to 0 the smaller the connectivity is and the closer to 1 the greater the connectivity. We can observe that in general the connectivity of both domains presents median values for almost all samples, and that in most of them the microporous phase is better connected than the macropores.

Figure 3

Numerical propagation of the electric field in digital rock models saturated with water. The colors indicate electric potential values (blue = 0 V, red = 12 V).

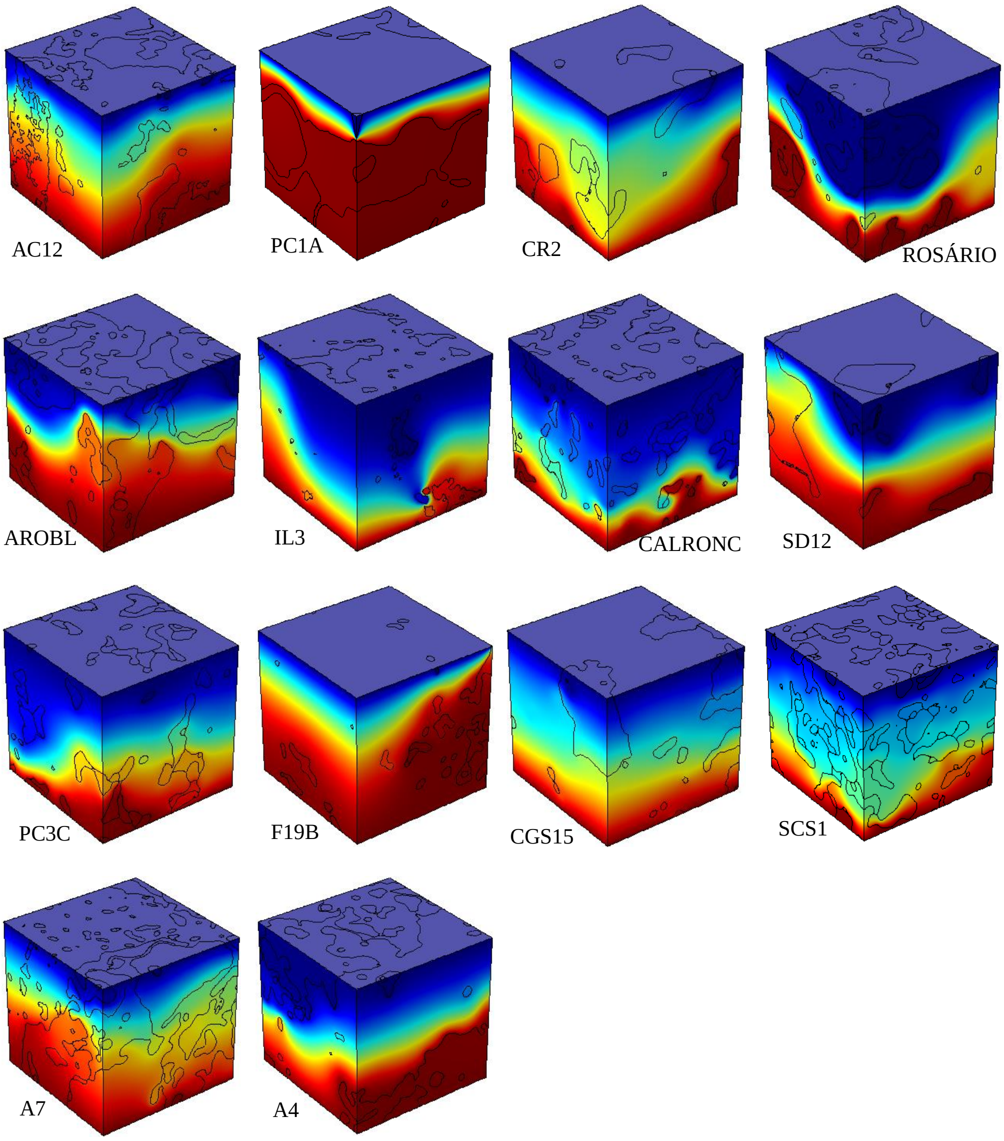
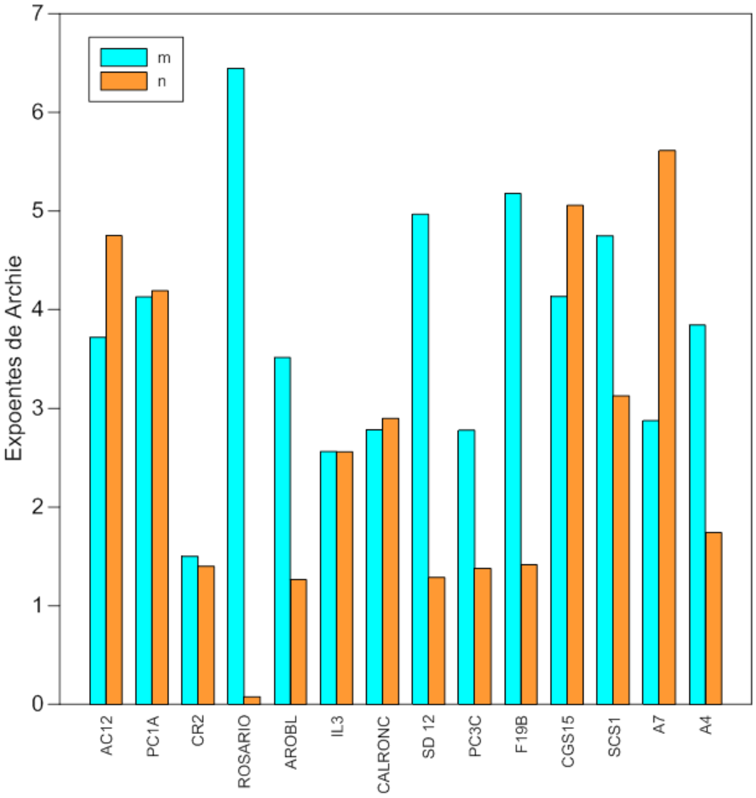


Figure 4 presents the values of Archie exponents (m and n) as estimated by numerical simulation of electric field propagation in digital rock models. It can be observed that the values of both exponents vary considerably from the classically adopted values (m = n = 2). Only by jointly observing the results for the volumetric fractions of the microporous and macropore phases, in addition to the macropore connectivity indices (PCI) and the microporous phase (ICFI), is it difficult to establish consistent relationships. For this reason, we will do a statistical analysis in order to investigate the influence of the volumetric fractions of the domains and the connectivity indices of these domains on the exponents of the Archie equation.

Figure 4

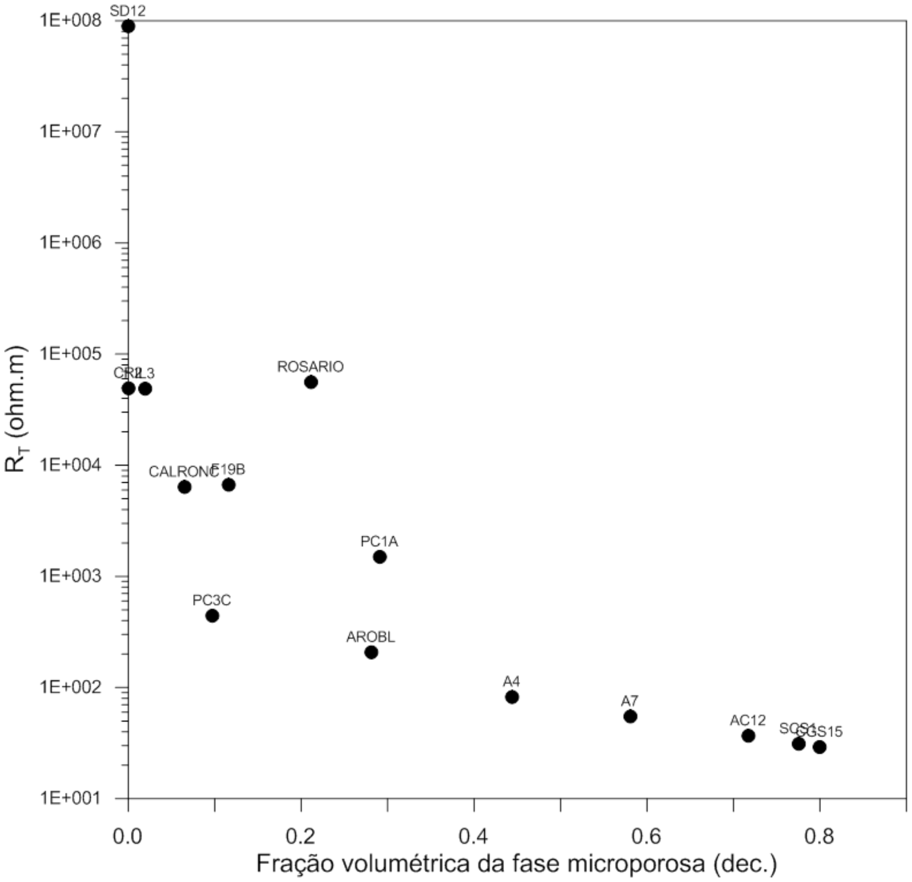
Estimated values for cementation and saturation coefficients by numerical simulation of electric field propagation in digital rock models.



Finally, the graph in Figure 5 illustrates the influence of the microporous phase on the resistivity of the rocks saturated with oil and irremovable water. As pointed out by Yao *et al.* (2013) and Harland *et al.* (2015), the resistivity of the rock decays exponentially with the increase of the microporous phase which, due to its high content of irremovable water, is always conductive. This result is also in line with Cerepi (2004) which states that the resistivity of the rock is influenced not only by porosity, but also by the microporous phase. We can observe from Figure 5 that the five samples with lower electrical resistivity correspond to those with a higher volumetric fraction of the microporous phase.

Figure 5

Relationship between the resistivity of the oil-saturated rock and the volumetric fraction of the microporous phase of the rocks analyzed.



4.1 STATISTICAL ANALYSIS

Applying regression of the piecewise linear type to the dataset, considering that the dependent variable is the exponent that one wants to analyze (m or n), and that the independent variables are the porosity of the macropores (Ø), the volumetric fraction of the microporous phase (FI), the connectivity index of the macropores (ICP) and the connectivity index of the microporous phase (ICFI), one arrives at an expression of the type of equation 9.

$$m\ (\text{ou}\ n) = a_0 + a_1 * \emptyset + a_2 * FI + a_3 * ICP + a_4 * ICFI \qquad (9)$$

Piecewise linear regression adjusts two linear functions to the data with multiple independent variables, separated by a breakpoint, i.e., the coefficients in equation 9 for m (or n) values lower than the breakpoint are different from those for values greater than the breakpoint. This regression applied with the cementation exponent as a dependent variable resulted in a coefficient of determination $R^2 = 0.94$ and a breakpoint equal to 3.8.

For $m < 3.8$ the coefficients in equation 9 are shown in Table 3.

Table 3

Regression coefficients for m < 3,8.

a_0	**a_1**	**a_2**	**to$_3$**	**to$_4$**
2.798717	-5.24515	1.799591	-0.491956	0.922209

For $m > 3.8$ the values of the coefficients of equation 9 are shown in Table 4.

Table 4

Regression coefficients for m > 3,8.

a_0	**a_1**	**a_2**	**to$_3$**	**to$_4$**
20.45969	24.39952	2.291167	-27.0111	-11.9788

Analyzing Table 3 we see that, for values of $m < 3.8$, FI and ICFI are directly proportional to the value of m (positive coefficients), while the porosity of macropores (Ø) and PCI are inversely proportional to [redacted]m. These results are in line with the statements of Olsen *et al.* (2008), Glover (2009, 2010), and Dasthian *et al.* (2015) and it follows from the fact that increased cementation reduces Ø and tends to reduce the interconnectivity of macropores. We also see that Ø and the volumetric fraction of the microporous phase (FI) are the most important variables, the first being more relevant than the second. In this case the ICP is the least important variable.

For values of $m > 3.8$ (Table 4) we see that Ø and FI have direct relation with m, while ICP and ICFI have inverse relation. In this case PCI and Ø are the most important variables, FI being the least important.

When piecewise linear regression was applied to investigate the dependence of the saturation exponent n Tables 5 and 6 present, respectively, the values of the coefficients for values of n smaller and larger than breakpoint equal to 2.6. The coefficient of determination for the regression of the saturation exponent was $R^2 = 0,90$.

Table 5

Regression coefficients for n < 2,6.

a_0	a_1	a_2	to$_3$	to$_4$
-4.37391	0.422333	-1.51671	6.059571	6.310355

Table 6

Regression coefficients for n > 2,6.

a_0	a_1	a_2	to$_3$	to$_4$
5.363513	-37.2848	3.136051	-12.4156	15.33984

For values of *n* < 2.6 (Table 5) we see that FI presents inverse relation with *n*, and this statement is consistent with Sen (1997). In this case Ø, ICP and ICFI have direct relation, ICFI and ICP being the most important variables and Ø the least important. This result demonstrates the importance of connectivity of the potentially conductive domains for the estimation of the saturation coefficient (*n*).

For *n* values > 2.6 (Table 6) FI and ICFI have direct relation with the saturation exponent, while Ø and ICP have inverse relation. This result agrees with Liu *et al.* (2015). In this case Ø is the most important variable and FI is the least important.

In all statistical analyzes carried out, it was found that the mineral matrix, being considered very resistive, does not influence the values of the Archie exponents, and this influence is reserved to the potentially conductive domains, such as the porosity of the macropores and the microporous phase.

5 CONCLUSIONS

This paper demonstrates how the porosity of macropores and micropores, in addition to their interconnectivities, influence the electrical properties of carbonaceous and sandy rocks. It is shown that the relationship between the cementation and saturation exponents of Archie's equation and the properties of the potentially conductive phases is linear in parts. Thus, there exists a linear relation for exponent values below a certain value and another linear relation for exponent values above that level. In addition, the influence of microporous phases (clay in the sandy rocks and micrite in the carbonaceous rocks) on the electrical conductivity of the investigated rocks is demonstrated.

In general, the cementation exponent is directly proportional to the volumetric fraction of the microporous phases and inversely proportional to the connectivity of the macropores, as previously reported in the literature. However, this article shows that the relationship of m with the porosity of the macropores and with the interconnectivity of the microporous phase is variable: while the porosity of the macropores is inversely proportional to m below a certain level (m = 3.8), this relationship is directly above this level. As for the interconnectivity effect of the microporous phase, it is shown that the relation with m is directly below the plateau and inversely above it. The most important variables are the porosity of the macropores and their interconnectivity, as well as the volumetric fraction of the microporous phase.

As for the saturation exponent, this article shows that there is a general direct relationship with the interconnectedness of the microporous phase, but a variable relationship with the porosity of the macropores, with their interconnectedness and with the volumetric fraction of the microporous phase. For values of n below a plateau (n = 2.6) the porosity of macropores and their interconnectedness maintain a direct relationship with n, while above this plateau the relationship is inverse. For the saturation exponent the variables of greatest influence are the porosity of the macropores and the interconnectivity of both potentially conductive domains (macropores and microporous phase).

ACKNOWLEDGMENTS

The first and third authors thank CAPES for awarding postgraduate scholarships. Thanks are also due to PETROBRAS and ANP, which, through R&I projects, provided the necessary financial support for the development of this research.

REFERENCES

Adebayo, A. R., H. Y. Al-Yousef, and M.A, Mahmoud, 2015. *An investigation of the effect of CO2-brine-rock interaction on determination of Archie's saturation exponent for carbon dioxide evaluation in carbonate reservoirs: Journal of Petroleum Science and Engineering*, 133, 665–676, doi: 10.1016/j.petrol.2015.05.005.

Archie, G. E., 1942. *The electrical resistivity log as an aid in determining some reservoir characteristics:* T. AIME, 146, 54–62.

Cerepi, A., 2004. *Geological control of electrical behaviour and prediction key of transport properties in sedimentary porous systems: Colloids and Surfaces A: Physicochem. Eng. Aspects*, 241, 281–298, doi: 10.1016/j.colsurfa.2004.04.049.

Dashtian, H., Y. Yang, and M. Sahimi, 2015. *Nonuniversality of the Archie exponent due to multifractality of resistivity well logs:* Geophys. Res. Lett., 42, 10,655–10,662, doi: 10.1002/2015GL066400.

Gholanlo, H. H., S. S. Yeganeh, and V. G. Dehrizi, 2018. *Saturation exponent determination by using genetic algorithm in carbonate reservoirs: A case study in Sarvak Formation:* Egyptian Journal of Petroleum, 27, 241–247, doi: 10.1016/j.ejpe.2017.07.013.

Glover, P., 2009. *What is the cementation exponent? A new interpretation:* The Leading Edge, January 2009, 82-85.

Glover, P. W. J., 2010. *A generalized Archie's law for n phases:* Geophysics, 75, no. 6, E247-E265, doi: 10.1190/1.3509781.

Glover, P. W. J., 2016. *Archie's Law – A reappraisal: Solid Earth Discuss.*, doi: 10.5194/se-2016-47.

Hamada, G. M., 2010. *Analysis of Archie's parameters determination techniques: Petroleum Science and Technology*, 28:1, 79-92, doi: 10.1080/10916460802706463.

Harland, S. R., R. A. Wood, A. Curtis, M. I. J. van Dijke, K. Stratford, Z. Jiang, W. Kallel, and K. Sorbie, 2015. *Quantifying flow in variably wet microporous carbonates using object-base. geological modeling and both lattice-Boltzmann and pore-network fluid flow simulations:* AAPG Bulletin, v. 99, no. 10, 1827–1860.

Liu, H., Y. Zhao, Y. Luo, Z. Chen and S. He, 2015. *Diagenetic facies controls on pore structure and rock electrical parameters in tight gas sandstone:* J. Geophys. Eng. 12, 587–600.

Mardi, M., H. Nurozi and S. Edalatkhah, 2012. *A water saturation prediction using artificial neural networks and an investigation on cementation factors and saturation exponent variations in an Iranian oil well:* Petroleum Science and Technology, 30:4, 425-434, doi: 10.1080/10916460903452033.

Olsen, C., T. Hongdul, and I. L. Fabricius, 2008. *Prediction of Archie's cementation factor from porosity and permeability through specific surface:* Geophysics, Vol. 73, no. 2, E81–E87, doi: 10.1190/1.2837303.

Sen, P. N., 1997. *Resistivity of partially saturated carbonate rocks with microporosity:* Geophysics, Vol. 62, no. 2, 415–425.

Sharifi, G. H., K. Saadat, E. Kazemzadeh, and H. Mahmoudian, 2012. *Measurement of Archie parameters of some carbonate cores at full reservoir conditions:* Journal of Chemical and Petroleum Engineering, 46, no. 1, 63-72.

Soleymanzadeh, A., P. K. Kaj, S. Kord, and M. Monjezi, 2021. *A new technique for determining water saturation based on conventional logs using dynamic electrical rock typing: Journal of Petroleum Science and Engineering*, 196, 107803, doi: 10.1016/j.petrol.2020.107803.

Winsauer, W. O., Shearin Jr., H. M., Masson, P. H. and M. Williams, 1952, *Resistivity of brine-saturated sands in relation to pore geometry:* AAPG Bulletin, 36 (2): 253-277.

Xiao, L., Z. Mao, G. Li and Y. Jin, 2013. *Estimation of saturation exponent from Nuclear Magnetic Resonance (NMR) logs in low permeability reservoirs:* Appl Magn Reson., 44, 333–347, doi: 10.1007/s00723-012-0366-1.

Yao, J., C. Wang, Y. Yang, R. Hu, and X. Wang, 2013. *The construction of carbonate digital rock with hybrid superposition method:* Journal of Petroleum Science and Engineering, 110, 263–267, doi: 10.1016/j.petrol.2013.10.005.