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Study of the low-frequency dispersion of permittivity and resistivity in tight rocks

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Abstract

This study investigated the frequency dispersion of the resistivity and permittivity in tight rocks of the Daanzhai Group, Jurassic formation, Sichuan Basin. Tight limestone cores were used in the experiment, and the frequency varied from 0.1Hz to 1kHzunder laboratory conditions. The permittivity and resistivity decrease as the frequency increases, but the changing rates of these two parameters are different, as the permittivity exhibits a more obvious dispersion than the resistivity at both low and high frequency. Over the whole frequency range, the change rate of the resistivity is very small and can even be neglected. The change rate of the permittivity, however, is very significant, and its difference reached several orders of magnitude. Besides this phenomenon, the frequency dispersion degree increases as the water saturation and concentration increase. Therefore, we establish a group of equations to describe this relationship between the frequency dispersion and water saturation, and water concentration. Unlike Archie's equation, which need multiple experimental parameters, the new formula can directly calculate the saturation from R_p and C_p or from D_R and D_C, only requiring two variables. Furthermore, frequency scanning test still implicates abundant information, which perhaps characterizes the pore structure, porosity, permeability and other properties of rocks or formations.

Keywords: litho-electrical experiment, resistivity, permittivity, frequency dispersion degree, water saturation, salinity, tight rock

Introduction

Resistivity and dielectric permittivity are important physical parameters that govern the propagation of electromagnetic fields (EMFs) in porous rocks. The resistivity of rocks has been researched for several centuries, and hundreds of thousands of studies have been published on them.[1] First presented his litho-electric experiment results and provided an equation to relate the resistivity and saturation of rocks. Thereafter, one can not only qualitatively evaluate the fluids in rocks but also quantitatively calculate the amount of water and hydrocarbons. Generally, the resistivity and permittivity of the rock are functions of the chemical composition, density, porosity, water saturation, in homogeneity, polycrystallinity, lithology and component geometries, which in turn are related to the particle size distribution (or rock texture), rock bulk density, and shape of the rock particles.[2–7] However, it is difficult to confirm the exact contribution of each physical and petro logical parameter to a sample's measured dielectric constant. Of all of these aspects, the most dominant factor affecting the dielectric permittivity of rock is its water saturation, including both bound and free water.

The frequency dispersion of the complex dielectric constant provides useful information for geophysicists, petro physicists, and any person interested in rocks. Most published studies have focused on the properties of the dielectric constant at high frequency, usually in the range of kHzto MHz, or even GHz.[8–14] However, the phenomenon of low-frequency dispersion (LFD), which is widely observed in many materials, was not been properly recognized until its discovery by the Chelsea Dielectrics Group[15] and the investigation of its properties with increasing precision, as described in the book Dielectric Relaxation in Solids (DRS). Earlier studies proved that most rocks and minerals show dielectric dispersion in the low-frequency region from a few Hz to several MHz.[16–18] At low frequencies, the dielectric dispersion of geological materials is believed to be caused by the polarization associated with charge buildup at the grain boundaries or grain imperfections. However, grain sizes and their distribution also control the frequency-dependent ε' values of the geological samples.[19,20] Many studies confirm that sandstones and other geological materials exhibit [22] dielectric dispersion at low frequencies.[16,20,21,23–27]

Although the Cole-Cole model is a relatively universal equation to depict the polarization and relaxation process for most media, there are still many mechanisms that are not fully understood. Summarized three types of polarization in rocks, namely, electronic, orientational and interfacial, and they noted that the predominance of these regimes depends on the frequency of the external electric field. Each type of polarization will vanish past a certain frequency, which is determined by the inertial moment of the particles in question, frictions and electrostatic forces. They expressed that the electronic polarization, corresponding to rock permittivity, occurs at a range of 1Hz to approximately 1×10^{8} Hz; molecular orientation, corresponding to the water molecular permittivity, occurs at range of 1Hz to approximately 1×10^{10}Hz; and interfacial polarization, corresponding to pore geometry and ions, occurs at a range of 1Hz to approximately 1×10^{16}Hz.

Obviously, in the low-frequency domain, the dielectric permittivity dispersion bears abundant information about the matrix, shale, fluid and pores, and even the geometry of the pores, their distribution, and the connectivity of the pore throat. For the case of tight reservoirs, a low frequency should be more useful to disclose the mysteries hidden in the rocks. This paper presented an experiment on tight limestone from Daanzhai Group, Jurassic formation, Sichuan Basin, and discussed the results in detail. In this paper, we mainly focused on the characteristics of the permittivity dispersion and its relationships with the saturation and concentration. In addition, we established a group of equations to describe the relationships of the frequency dispersion with the resistivity and permittivity. We defined two variables, D_R and D_C, to depict the decreasing rate of R_p and C_p. Based on these two variables, we established a formula to calculate the saturation of samples.[28]

Experiment tests

a. General description of experiment

We selected tight lime stones out of 18 different lithological rocks, as shown in Figure 1. The specifications of it were listed in Table 1. To simulate the environment of the borehole, unlike usual cores, the samples were 15cm height, 10cm in diameter, and with a hole in middle of the cylinder, named the mid-hole, with a diameter of 1.5cm, through which the electrodes were placed while measuring. Artificial mud was also injected into this hole to assure that the electrical current can penetrate into the core.

Figure 1 Sample No. 16 of tight rocks from 18 different lithological rocks, all cut with dimensions of 15cm in height and 10cm in diameter, with a mid-hole of 1.5cm in diameter. No. 16 was drilled from Daanzhai Group, Jurassic formation, middle region of Sichuan Basin. Its porosity is 5.90%, and permeability is $0.013\times10^{-3}\mu m^2$.

Table 1 Basic parameters of tight rock sample

No	Height /Cm	Diameter /Cm	Mid-hole diameter /Cm	Dried weight /G	Volume /Cm^3	Porosity /%	Permeability /$\times10^{-3}\mu m^2$
16	15.00	10.47	1.43	3048	1266.71	5.90	0.013

We used a LCR Analyzer to detect the resistivity and dielectric permittivity, and BH-II high pressure vacuum saturation device to saturate samples with different concentrations of NaCl solute.

We selected carbon fiber as electrodes, which show high electrical stability even in high-concentration salt solutions. First, the artificial mud was injected into the mid-hole, and then the electrodes were placed into the mid-hole. The mud can conduct the current into the core so that the electromagnetic field would be almost homogeneously distributed around the borehole at a relative shallow distance from the mid-hole. This configuration is very similar to real borehole environment of well logging operations.

b. Experiment processing

First, we prepared three different concentrations of NaCl solution (C_w): 0.125mol/L, 0.25mol/L, and 0.5mol/L. Secondly, the samples were dried in microwave oven; and then they were put into a container of BH-II, and saturated with NaCl solution of different C_w. Subsequently, the electrode was placed into the mid-hole of the cores, and the last step was to switch on LCR Analyzer, the resistivity and permittivity could be shown on the screen together. The LCR can provide these two parameters Rs, C sin serial and R_p, C_p, in parallel modes, respectively, where the subscript "s" means series mode, and "p" indicates a parallel mode. For actual situation, generally, borehole is divided into flushed zone, transition zone and uncontaminated zone. The current conducts through these three zones in parallel, so during the experiment, we measured R_p and C_p in different saturation and NaCl concentration, and the frequency ranged from 0.1Hz to 1kHz. Table 2 listed the dry weight, saturation and concentration of NaCl solution.

Table 2 Water content, saturation and dry weight of Sample

0.125 mol/L	Dry weight/g	3172.0	3128.0	3108.0	3094.0	3050.0
	Saturation/%	88.36	56.49	42.01	31.87	0.00
0.25 mol/l	Dry weight/g	3178.0	3138.0	3116.0	3070.0	3050.0
	Saturation/%	92.71	63.74	47.80	14.49	0.00
0.5 mol/l	Dry weight/g	3182.0	3148.0	3116.0	3084.0	3050.0
	Saturation/%	95.60	70.98	47.80	24.62	0.0

Parameter measurement and data analysis

a. Measurement of resistivity and permittivity

During this experiment, we tested the sample with five different saturation, three different concentration, and frequency ranged from 0.1Hz to 1 kHz (the increment is on a logarithm scale), so totally 15 group, each 105 data points of resistivity and permittivity were recorded. Part of the data were presented in Table 3, in which $R_p1,R_p2,\ldots,R_p5$, correspond to resistivity in parallel in five different saturation, and $C_p1,C_p2,\ldots,C_p5$ correspond permittivity in parallel. Data in concentration of 0.25mol/L and 0.5mol/L were not listed out take account of the length of the paper Table 3.

b. Data analysis

We wanted to resolved four questions based on the above experimental results:

i. What are the characteristics of the frequency dispersion of these two variables in the range of 0.1Hz- 1 kHz?

ii. What is the relationship between the frequency dispersions of these two variables at different saturations?

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iii. What is the relationship between the frequency dispersions of these two variables at different concentrations?

iv. What are the characteristics of the frequency dispersions of these two variables at high and low frequencies?

Table 3 Part of resistivity data with concentration of 0.125mol/L (Ω·m)

F/Hz	Rp1	Rp2	Rp3	Rp4	Rp5
	Sw1=88.36%	**Sw2=56.49%**	**Sw3=42.01%**	**Sw4=31.87%**	**Sw5=0%**
0.1	1.18E+03	1.27E+03	2.01E+03	2.62E+03	8.14E+03
24	8.38E+02	1.04E+03	1.61E+03	2.15E+03	6.88E+03
35	8.32E+02	1.03E+03	1.60E+03	2.14E+03	6.85E+03
155.6	8.10E+02	1.01E+03	1.57E+03	2.11E+03	6.77E+03
192	8.07E+02	1.00E+03	1.57E+03	2.11E+03	6.76E+03
225.7	8.05E+02	1.00E+03	1.57E+03	2.10E+03	6.75E+03
280	8.02E+02	9.99E+02	1.56E+03	2.10E+03	6.73E+03
628	7.93E+02	9.88E+02	1.55E+03	2.08E+03	6.69E+03
1000	7.88E+02	9.82E+02	1.54E+03	2.07E+03	6.66E+03
F/Hz	**Cp1**	**Cp2**	**Cp3**	**Cp4**	**Cp5**
	Sw1=88.36%	**Sw2=59.49%**	**Sw3=42.01%**	**Sw4=31.87%**	**Sw5=0%**
0.1	5.10E-04	3.14E-04	2.05E-04	1.26E-04	2.58E-05
24	3.82E-07	2.46E-07	1.33E-07	8.12E-08	2.13E-08
35	2.43E-07	1.59E-07	8.50E-08	5.20E-08	1.38E-08
155.6	4.36E-08	3.02E-08	1.65E-08	1.05E-08	2.83E-09
192	3.45E-08	2.42E-08	1.31E-08	8.56E-09	2.30E-09
225.7	2.89E-08	2.05E-08	1.13E-08	7.24E-09	2.02E-09
280	2.29E-08	1.63E-08	9.06E-09	5.93E-09	1.65E-09
628	9.68E-09	7.14E-09	4.14E-09	2.79E-09	8.44E-10
1000	5.97E-09	4.49E-09	2.66E-09	1.84E-09	5.99E-10

Characteristics of frequency dispersion: Based on the results of experiment, Figures 2-4 show the relationships of resistivity and permittivity's. Frequency. Figure 2 exhibits five curves, and each one corresponded to different saturation that listed in Table 2. All of these 5 curves were with concentration of 0.125mol/L. Figure 3 shows similar curves corresponding concentration of 0.25mol/L, and Figure 4 shows curves with concentration of 0.5mol/L. From these figures, we can summarize the following laws:

i. When completely saturated, the resistivity decreases with the increasing frequency, and shows almost a direct line on a semi-logarithm plot. Very little change occurred over the range from 0.1 Hz to 1 kHz. The permittivity also decreases as the frequency increases, but the decreasing line is a semi-parabolic or logarithmic type, with a gradient that is obviously larger than that of resistivity.

ii. The resistivity and permittivity show the same changing trend vs. different saturations; that is, they all decrease with the increase of saturation.

iii. However, different saturations result in different change rate; the higher the saturation is, the larger the change in these two variables.

iv. Figure 4-5 show similar change trend with Figure 3.

Based on these experimental data, we have established a set of new formulas between R_p and C_p and frequency, as follows.

C_w= 0.125mol/L

S_{w1}=88.36%:$R_p1=958.57\times F^{-0.035}$($R^2$=0.8823), $C_p1=2\times10^{-5}\times F^{-1.239}$($R^2$=0.9983);

S_{w2}=59.49%:$R_p2=1134.7\times F^{-0.025}$ (R^2=0.9335), $C_p2=1\times10^{-5}\times F^{-1.237}$($R^2$=0.9976);

S_{w3}=42.01%:$R_p3=1758.1\times F^{-0.024}$ (R^2=0.8875), $C_p3=8\times10^{-6}\times F^{-1.233}$($R^2$=0.9965);

S_{w4}=31.87%:$R_p4=2319.3\times F^{-0.020}$ (R^2=0.8758), $C_p4=5\times10^{-6}\times F^{-1.224}$($R^2$=0.9955);

S_{w5}=0%:$R_p5=7310.2\times F^{-0.017}$ (R^2=0.8710), $C_p5=1\times10^{-6}\times F^{-1.192}$($R^2$=0.9952);

Formulas for concentrations of 0.25mol/L and 0.5mol/L had similar exponent form, and were omitted for sake of concise paper. To describe the mathematical relation, we defined two variables.

i. Frequency dispersion of resistivity, DR: an exponent that depicts the gradient of the resistivity decrement with the

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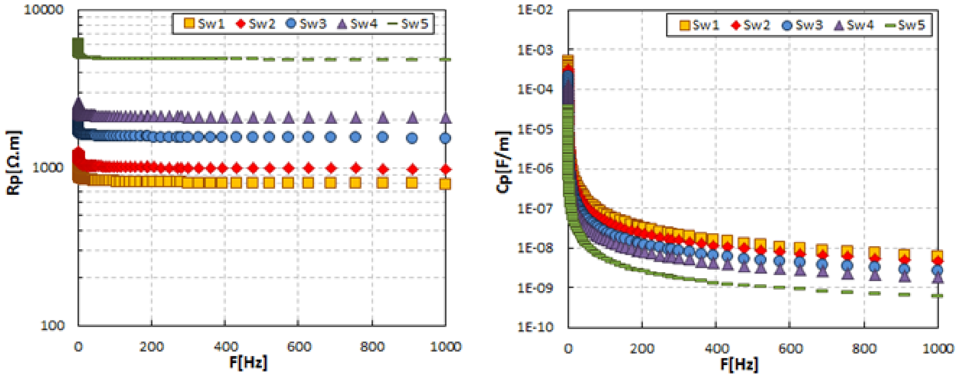
increasing frequency. The subscript R means resistivity.

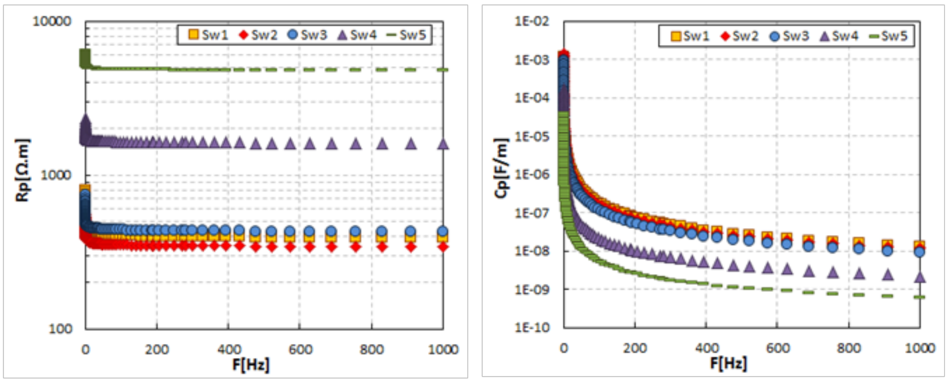
ii. Frequency dispersion of permittivity, DC: an exponent that depicts the gradient of permittivity decrement with the increasing frequency, denoted by DC. The subscript C means dielectric permittivity.



a. Frequency dispersion of resistivity **b. Frequency dispersion of permittivity**

Figure 2 Frequency dispersion of Rp and Cp with a concentration of 0.125mol/L.

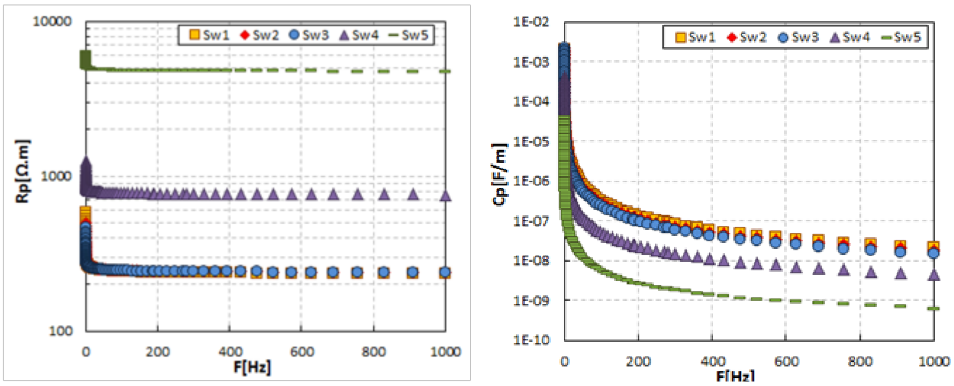
Left plot: Frequency dispersion of resistivity at different saturations. Each curve obeys almost the same law; that is, the resistivity decreases as the frequency increases, but the changes are near zero. Right plot: Frequency dispersion of permittivity at different saturations. There are very significant differences from the corresponding resistivity curves, especially in the low-frequency domain.



a. Frequency dispersion of Rp **b. Frequency dispersion of Cp**

Figure 3 Frequency dispersion of Rp and Cp at a concentration of 0.25mol/L.

Left plot: Frequency dispersion of resistivity at different saturations. Each curve obeys almost the same law; that is, the resistivity decreases as the frequency increases, but the changes are near zero. Right plot: Frequency dispersion of permittivity at different saturations with very significant changes from the corresponding resistivity curves, especially in the low-frequency domain. In addition, at the same saturation, the higher the concentration of NaCl solution in the sample is, the larger is the change in the permittivity curves.



a. Frequency dispersion of Rp **b. frequency dispersion of Cp**

Figure 4 Frequency dispersion of Rp and Cp at a concentration of 0.5mol/L.

Left plot: Frequency dispersion of resistivity at different saturations. Each curve obeys almost the same law; that is, the resistivity decreases as the frequency increases, but the changes are near zero. Right plot: Frequency dispersion of permittivity at different saturations, with very significant changes relative to the corresponding resistivity curve, especially in the low-frequency domain. At the same saturation, the higher the concentration of NaCl solution in the sample is, the larger is the change in the permittivity curves.

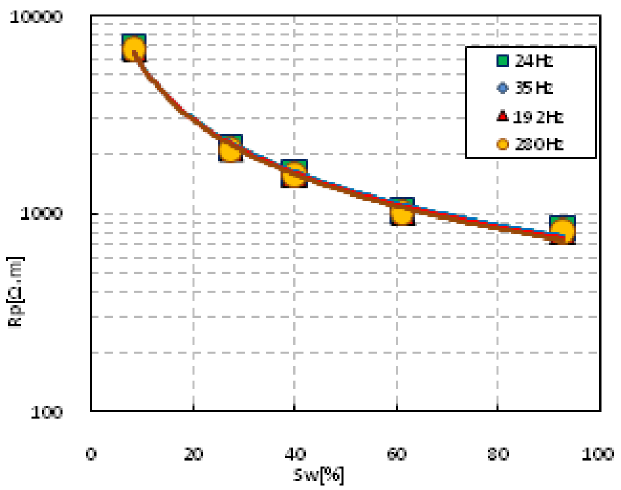


Figure 5 Relation between Sw and Rp. Resistivity decreases as saturation increases, but at the same saturation, the resistivity does not vary significantly with the frequency changes.

A general equation for R_p and C_p, based on the above formulas, can be rewritten as follows:

$$Rp = A \times F^{-D_R} \tag{1}$$

$$Cp = B \times F^{-D_C} \tag{2}$$

Where A and B are constant, which can be got through least-square method.

It is well known that Debye presented a dielectric model in 1912, namely Debye Model, to clarify the relation of dielectric and frequency,[22] has more extensive adaptability. Comparing to these two classical models, equation (2) is much easier and succinct.

i. **Relationship between saturation and R_p, C_p:** From the above figures and discussion, we can conclude that although the measurement frequency is different, R_p and C_p illustrate almost the same trend of variation as functions of the saturation and concentration. We therefore established certain equations to directly calculate the saturation using R_p or C_p, as shown in Figure 5, Figure 6. Comparing these two figures, we find that at the same saturation, resistivity has nearly the same value at different measurement frequencies; as for C_p, however, has different values at different frequencies.

F=24Hz, $S_w = 44257R_p^{-0.896}$ $R^2 = 0.9931$, $S_w = 2E\text{-}09C_p^{1.2144}$ $R^2 = 0.9978$

F=35Hz, $S_w = 44285R_p^{-0.897}$ $R^2 = 0.9933$, $S_w = 1E\text{-}09C_p^{1.2108}$ $R^2 = 0.9974$

F=192Hz, $S_w = 44340R_p^{-0.904}$ $R^2 = 0.9937$, $S_w = 2E\text{-}10C_p^{1.1455}$ $R^2 = 0.9974$

F=280Hz, $S_w = 44303R_p^{-0.905}$ $R^2 = 0.9937$, $S_w = 2E\text{-}10C_p^{1.1114}$ $R^2 = 0.9973$

In addition to the R_p and C_p, we should also note that D_R and D_C are different for different saturations, and the values of these two parameters at different saturations and concentrations are listed in Table 4. The general rule is that the values are proportional to the saturation. The difference between D_R and D_C is that the latter is much larger than the former at the same saturation by approximately two orders of magnitude.

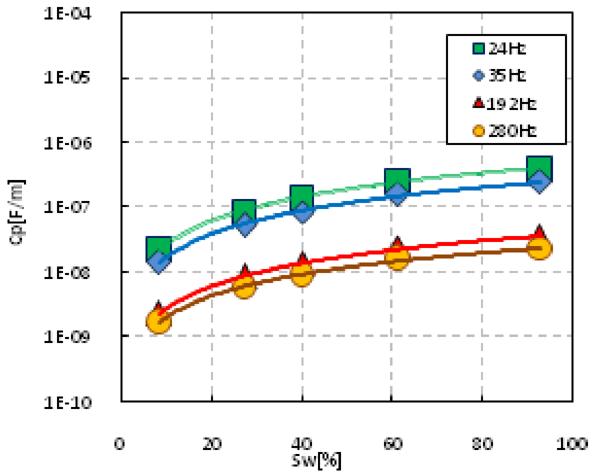


Figure 6 Relation between Sw and Cp. Permittivity increases with the saturation, and at the same saturation, the permittivity decreases as the measurement frequency increases.

Table 4 $D_R$and$D_C$with different saturations at 0.125mol/L

Para.	Sw1	Sw2	Sw3	Sw4	Sw5
DR	0.035	0.025	0.024	0.02	0.017
DC	1.239	1.237	1.233	1.224	1.192

This means that there is some implicit relationship between D_R, D_C and the saturation. Figure 7 shows the relationship of S_w *vs*. D_R at concentrations of 0.125mol/L, 0.25mol/L, and 0.5mol/L, and Figure 8 shows the relationship of S_w *vs*. D_C at concentrations of 0.125mol/L, 0.25mol/L, and 0.5mol/L.

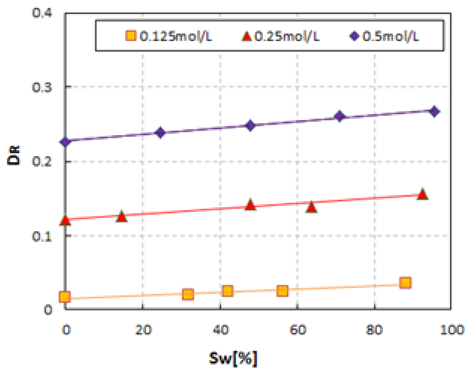


Figure 7 Sw *vs*. D_R at different concentrations.

The general rule of exponent D_R is that the higher the concentration is, the higher the value of D_R is at the same saturation. Additionally, D_R increases with the saturation at the same concentration. The concentration has a much greater effect on the resistivity frequency dispersion exponent than the saturation.

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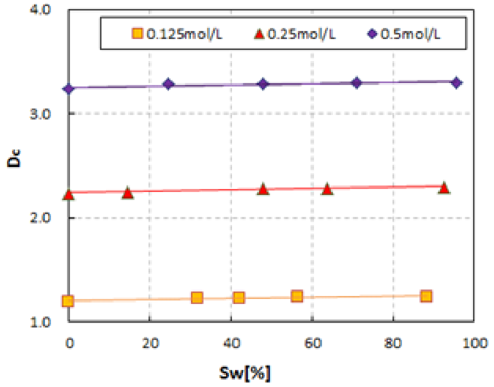

Figure 8 Sw *vs.* D_C at different concentrations. The general rule of exponent D_c is that the higher the concentration is, the higher the value of D_c is at the same saturation. Additionally, D_c is nearly unchanged as the saturation increases at the same concentration. Obviously, the concentration has a much greater effect on the resistivity frequency dispersion exponent than the saturation. Note: A constant of 0.1 was added to the data of D_R at a concentration of 0.25mol/L and 0.2 was added at 0.5mol/L to more easily distinguish the curves in the figure. The data of D_C were treated in same manner, with 1 added to the concentration of 0.25mol/L and 2 added to 0.5mol/L.

Based on these two figures, we can see that the saturation can be calculated from D_R and D_C, in accordance with the below equations. The mechanism of this phenomenon will be discussed in another paper.

C_w=0.125mol/L: $S_w=4589.0D_R-67.308$, $R^2=0.9343$, $S_w=1485.4D_C-1775.8$, $R^2=0.7828$;

C_w=0.250mol/L: $S_w=2652.2D_R-321.20$, $R^2=0.9540$, $S_w=1444.0D_C-3233.9$, $R^2=0.9123$;

C_w=0.500mol/L: $S_w=2255.9D_R-512.11$, $R^2=0.9871$, $S_w=1460.5D_C-4744.0$, $R^2=0.7826$.

These equations proofed that frequency dispersion can be used to calculate saturation.

Conclusion

Through the measurement of R_p and C_p of tight rock sample under different saturation and concentration in the frequency range from 0.1Hz to 1kHz, the properties of R_p and C_p were investigated in detail. From the results of this experiment, we have discovered some characteristics of the frequency dispersion of resistivity and permittivity. Furthermore, a set of equations and variables to depict the dispersion laws have been constructed in this paper.

We summarize the findings as follows:

i. Under the same conditions, the frequency dispersion degree of resistivity is much less than that of permittivity in the whole frequency range;

ii. The frequency dispersion exponents of resistivity, DR, and permittivity, DC, increase with the saturation;

iii. The change rates of Rp and Cp increase with the concentration

iv. Based on DR and Dc, a set of novel equations have been established to calculate water saturation.

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Nomenclature

F : Frequency, Hz.

C_w: Concentration of NaCl solution, mol/L;

C_p: Permittivity, F/m;

R_p: Resistivity, Ω·m;

K: Electrode coefficient, cm;

S_w: Saturation of water;

D_R: Dispersion exponent of resistivity, dimensionless;

D_C: Dispersion exponent of permittivity, dimensionless;

A: Coefficient of resistivity, Ω·m;

B: Coefficient of permittivity, F/m;

Conflict of interest

The author declares no conflict of interest.

References

1. Archie GE. The electrical resistivity log as an aid in determining some reservoir characteristics. *Transactions of the American Institute of Mining and Metallurgical Engineers*. 1942;146(1):54–61.
2. Alex ZC, Behari J. Complex dielectric permittivity of soils as function of frequency, moisture and texture. *Indian J Pure and Applied Physics*. 1996;34:319–323.
3. Alex ZC, Behari J. Laboratory evaluation of permittivity of soils. *Int J Remote Sensing*. 1998;19(7):1335–1340.
4. Wang JR, O Neill PE, Jackson TJ, et al. Multi–frequency measurements of the effects on soil moisture soil texture and surface roughness. IEEE Trans. Geo Sci Remote Sensing Ge. 1983;21(1):44–50.
5. Pelton WH, Smith BD, Sill WR. Interpretation of complex resistivity and dielectric data. *J part II: Geophysics Trans*. 1984;29(4):11–45.
6. David PL, Kevin MF. Influence of pore fluid chemistry on the complex conductivity and induced polarization response of Berea sandstones. *J Geophysics Research*. 2001;106(B3):4079–4090.
7. Seleznev N. Dielectric mixing laws for fully and partially saturated carbonates rocks. *SPWLA 45th Annual logging symposium*. Netherlands, 2004.
8. Clark B, Martin GL, Jacques J, et al. A dual depth resistivity measurement for FEWD. Trans. 28th SPWLA Annual Logging Symposium. USA, 1988.
9. Clark B, David F Allen, David L, et al. Electromagnetic propagation logging while drilling:theory and experiment, SPE formation evaluation. 1990;5(3):263–271.

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10. Bonner S, JR Tabanou, JP Seydoux, et al. New 2–MHz multiarray borehole compensated resistivity tool developed for MWD in slim holes. *SPE Annual technical conference and exhibition*. USA, 1995.
11. Seleznev N, Boyd A, Habashy T, et al. Dielectric mixing laws for fully and partially saturated carbonate rocks. *SPWLA Annual Logging Symposium*. Netherlands, 2004.
12. Seleznev N, Tarek M, Austin. Formation properties derived from a multi–frequency dielectric measurement. *SPWLA 45th Annual logging symposium*. Mexico, 2006.
13. Anderson B, BarberT, Lüling M. Observations of large dielectric effects on induction logs, or can source rocks be detected with induction measurements. *SPWLA Annual Logging Symposium*. Mexico, 2006.
14. Anderson B, Barber T, Lüling M, et al. Identifying potential gas–producing shales from large dielectric permittivities measured by induction quadrature signals. *SPWLA Annual Logging Symposium*. 2008.
15. AK Jonscher. Dielectric Relaxation in Solids. London: Chelsea Dielectrics Press; 1983.
16. Saint Amant, MDW Strangway. Dielectric properties of dry geologic materials. *Geophysics*. 1970;35(4):624–645.
17. Knight RJ, A Nur. The dielectric constant of sandstones 60 KHz to 4 MHz. Geophysics. 1987;52(2):644–654.
18. Peter T Wu, John RL, Brain Clark, et al. Dielectric–independent 2–MHz propagation resistivities, SPE 74th Annual technical conference and exhibition. USA, 1999.
19. Feng S, PN Sen. Geometrical model of conductive and dielectric properties of partially saturated rocks. *Journal of Applied Physics*. 1985;58:3236–3243.
20. Lesmes DP, FD Morgan. Dielectric spectroscopy of sedimentary rocks. *Journal of Geophysical Research*. 2001;106(B7):13329–13346.
21. Lesmes DP, KF Frye. The influence of pore fluid chemistry on the complex conductivity and induced polarization response of Berea sandstone. *Journal of Geophysical Research*. 2001;106(B7):4079–4090.
22. Cole KS, RH Cole. Dispersion and absorption in dielectrics. I. Alternating current characteristics. *Journal of Chemical Physics*. 1941;9:341–351.
23. Taherian MR, WE Kenyon, KA Safinya. Measurement of dielectric response of water–saturated rocks. *Geophysics*. 1990;55(12):1530–1541.
24. Dias CA. Developments in a model to describe low–frequency electric polarization of rocks. *Geophysics*. 2000;65(2):437–451.
25. Sengwa RJ, A Soni, B Ram. Dielectric behavior of shales and calcareous sandstone of Jodhpur region. *Indian Journal of Radio and Space Physics*. 2004;33(5):329–335.
26. RJ Sengwa, A Soni. Low–frequency dielectric dispersion and microwave dielectric properties of dry and water–saturated limestones of the Jodhpur region. *Geophysics*. 2006;71(5):269–277.
27. Emmanuel Toumelin, Carlos torres–verdín. Pore–scale simulation of kHz GHz electromagnetic dispersion of rocks:effects of rock morphology, pore connectivity, and electrical double layers. *SPWLA 50th annual logging symposium*. USA, 2009.
28. Debye PW. Polar Molecules, Chemical Catalog Co. USA, 1929.

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