



# Synthetic mixture of sand and shale: how conductor (shale) and saturation influence electrical characteristics

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## Abstract

In the petroleum sector, spectral-induced polarization (SIP) can detect low-frequency electrical characteristics in rocks without causing any damage. Measurements from 1 mHz to 100 kHz were conducted at ambient temperature for synthetic shale sand combinations from Gabel El-Galala, Cairo, Egypt. Because of an increase in the relative conductor (shale) concentration despite a reduction in the relative insulator (sand) concentration, and the effect of increasing saturation, this is the first study to explain the electrical impact of shale sand combination. We will also look into its saturation and frequency to further model and analyze shale with electrical characteristics. Both conductivity and impedance decrease regarding sand's presence. The dielectric constant increases with increasing shale level and saturation below the percolation threshold but drops beyond it. Material rich in shale has lower impedance than material rich in sand. Concentrating and saturating the shale in the synthetic sand enhanced its electrical conductivity. Ionized liquid and the conductive minerals present in shale also contribute to this improvement. The mixture's electrical characteristics improved significantly as the frequency rose. Low-frequency analysis shows that the samples have high conductive and dielectric constants. These investigations could improve oil and gas recovery by illuminating the electrical characteristics of the reservoir rock.

**Keywords** Synthetic shale sand mixtures · Electrical conductivity · Dielectric constant · Saturation · Conductor · Frequency dispersion

## Introduction

Shale formations have gained significant attention in the oil and gas industry due to their potential as a source of

unconventional hydrocarbons (Gomaa 2022a, 2022b, 2022c, 2021; Capozzoli et al 2022; Abd El Aziz and Gomaa 2022a, 2022b; Gomaa et al 2021; Ammar et al 2021). However, the characterization of shale formations is challenging due to their complex mineralogical composition and highly variable characteristics (Grant 1958). A promising method for characterizing shale formations and water-bearing formations is electrical measurements. Several studies have investigated the electrical characteristics of shale rocks and their correlation with hydrocarbon content (e.g. Waxman and Smith, 1968). The details will be discussed in the following sections.

Several studies have investigated the electrical characteristics of shale and sand mixtures (Vinegar and Waxman 1984; Titov et al. 2004), but the effect of varying levels of conductor and saturation on the electrical characteristics of synthetic shale sand mixtures has not been extensively explored (Jougnot et al. 2010; Revil et al. 2013). Therefore, this study aims to investigate the electrical characteristics of synthetic shale sand mixtures under different conditions of shale content and saturation.

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Shale is a type of elastic sedimentary rock that forms in environments by gentle transporting currents and became compacted. The environment of deposition, which determines the grain characteristics that influence porosity and permeability, is generally what determines the quality of shallow buried reservoirs and the initial pore network of newly deposited sediments. Shale is a fine-grained mixture of colloidal or clay-sized particles which frequently contains a substantial quantity of minerals made up of clay. Shales are structured in bands of tetrahedron-silica and octahedron-alumina, as well as the surface of clay minerals usually contains a large number of negatively charged charges.

Shale and sand are both geological materials, but sand is an insulator while shale is a conductor. Insulators are poor conductors of electricity and do not allow charges to move easily through them. Because the electrons in insulators have strong bonds to their nuclei and lack sufficient energy for traveling freely, insulators cannot conduct electricity. On the other hand, conductors are materials that have free electrons and allow charges to move relatively freely through them. This is because the electrons in conductors are not tightly bound to their atoms and are able to move around more easily. Semiconductors are another category of materials that have characteristics between those of conductors and insulators. They have some free electrons, but not enough to allow for easy conduction of electricity. Understanding the characteristics of different materials and their electrical behavior is crucial for developing new technologies and improving existing ones. When an insulating substance gets overcharged, it cannot move readily and will remain in place for an extended amount of time. This is because the electrons in insulating materials are tightly bound to their atoms and cannot move freely to neutralize the charge. Excessive charge placed on a conductor, on the other hand, would quickly stream aside due to mutually exclusive repelling from preexisting charges. Due to their unrestricted ability to move, electrons in conductors will disperse equally throughout the conductor to reduce the attraction forces that exist between them.

The electrical characteristics of the mixture are influenced by the relative concentrations of the two components. The electrical conductivity of a shale and sand mixture is changed by the presence of clay minerals. However, further research would be needed to determine the specific electrical effects of changing the relative concentrations of shale and sand in a mixture and the salinity.

The interrelationships between electrical characteristics of conductor and insulator materials, including conductivity, dielectric constant, and impedance, are important to consider when evaluating and modeling materials such as shale (Gomaa 2022a, 2022b, 2022c; Capozzoli et al 2022,). The interrelationships between the electrical properties of

conductor and insulator materials are also greatly influenced by saturation effects and frequency, which can also have an impact on how mixtures of materials behave (Abd El Aziz and Gomaa 2022a, 2022b; Gomaa 2021; Gomaa et al 2021; Ammar et al 2021). Generally, the electrical characteristics of mixtures are highly dependent on shale composition, as well as the ionic concentration of the pore fluid (Wang and Zhang 2019; Gomaa et al. 2021). The distribution of shale in shaly reservoir sandstones also affects the electrical characteristics of the sandstones. Using a dataset of laboratory measurements on 11 samples, the study examined the impact of shale dispersion and saturation on the electrical properties of shaly sand samples. The results showed that saturation and shale distribution have an impact on the electrical characteristics of the sandy samples. The geological environment, the amount of quartz in the shale, the chemical composition of the conductor (shale), and the electrical characteristics of high organic shale are influenced by fluid saturation generally (Gomaa et al. 2021; Wang and Zhang 2019; Gomaa and Abou El-Anwar 2019).

The shale's considerable silica concentration resulted in high resistivity. This information may be useful in understanding the electrical characteristics of shale in a sand-shale mixture, but it does not provide a direct answer to the question of the significance of shale concentration in the mixture. Further research may be necessary to answer this question.

The electrical characteristics of shale can affect its use in oil and gas exploration. Shale is a form of sedimentary soil that is characterized by an elevated amount of organic matter and has the potential to hold oil and gas. Since shale is an anisotropic rock, its anisotropy has an impact on its electrical characteristics. This is caused by the simple fact that shale properties differ according to the angle in which they are measured. The anisotropy of shale is dominated by planes of weakness. Shale's pore structure, which changes depending on the geometry, size, and arrangement interactions of pores and openings in rocks, is a significant influence impacting resistivity (Abou El-Anwar and Gomaa 2013). The pore water distribution can vary depending on the direction in which they are measured if the shale is anisotropic. Therefore, the anisotropy of shale may affect its electrical properties, but further research is needed to determine the exact relationship between the two components of the mixture.

The electrical characteristics of shale are affected by its lithology, rock's composition, structure, porosity, and permeability. Overall, the most important electrical characteristics to consider in shale evaluation are resistivity, electrical conductivity, dielectric constant, and impedance properties. These characteristics can provide information about shale composition, porosity, permeability, and petrological features (He et al. 2017).

The study used samples with different shale content by weight and with the same compaction stress. The resistivity of the samples decreases with shale content and with compaction stress (Osterman et al. 2019).

Since sand is an insulator (or semi-insulator) and shale is a conductor, increasing the concentration of sand in the mixture would increase the overall insulator concentration, while decreasing the concentration of shale would decrease the overall conductor concentration (Gomaa and Abou El-Anwar 2019). The electrical properties of the combination, such as its conductivity or resistivity, may be influenced by this shift in the corresponding amounts of insulator and conductor materials. However, further research would be needed to determine the specific electrical effects of changing the relative concentrations of shale and sand in a mixture.

The total porosity of the mixture decreases as the insulator quantity increases (some pores are closed or blocked). The mixture electrical properties are impacted by the insulator content, such as shale or sand. Despite the comparatively conductive characteristics of shale, the electrical interaction caused by an increase in insulator concentration (sand) has been investigated. Since shale minerals are assumed to be electrically insulating, the conductivity of the surrounding water is used to calculate the shale's electrical conductivity (the water conductivity will be the dominant factor). The percentage of the counter-ion exclusion layer, which is relying on the specific area and volume of water in the counterion inclusion layer per unit weight of shale, controls the conductivity of the material.

Electrical impedances or admittances are frequency dependent make up Spectral induced polarization data. These parameters have complex values that can be written as phase and magnitude amounts, real and quadrature components, or combination. These characteristics exhibit both electrical conduction and polarization behavior (Bücker and Hördt 2013). Low frequency range of Spectral induced polarization data is usually analyzed and related to geophysical characteristics using empirical or phenomenological models (Kemna et al. 2012). Also, there are some progresses in mechanistic models evolution in recent years Revil and Florsch 2010). The bulk of research still relies on employing empirical models to formulate variable relationships (Weller et al. 2013; Slater 2007).

Chelidze and Gügüen (1999) discussed the analysis for heterogeneous media on the presence of polarization theories. These investigations demonstrate that electrical spectroscopy can serve to describe frequency spectra, for rocks carrying water and porous material using complex dielectric constant or conductivity. Furthermore, dry rocks are an insulator that with a conductivity of  $\sim 10^{-10}$  S/m or less, whereas the conductivity of saturated samples might be  $\sim 1$  S/m. This makes it difficult to quantify rock electrical characteristics (Jougnot et al. 2010; Gomaa 2022a, b, c).

In this context, the effect of conductor (shale) and saturation on the electrical characteristics of synthetic shale sand mixtures is of particular interest. Synthetic mixtures are commonly used to simulate the characteristics of shale formations and investigate their behavior under controlled conditions. We will try to show that the addition of sand to shale (or vice versa) can significantly alter the electrical characteristics of the mixture due to the presence of conductive minerals in shale. The saturation level of the mixture also may affect its electrical properties, as the presence of ions in water can enhance the electrical conductivity of the mixture.

## Methods and calculations used

### Samples location

The specimens were taken from Gebel El-Galala in Egypt's Eastern Desert, which is located north and west of the Gulf of Suez (Fig. 1). Ain-Sokhna Road is composed of crystalline rocks from the Precambrian era and is non-conformably covered by the Araba and Naqus formations (Fig. 1). Sandstones, which range in grain size from very fine to coarse and have irregularly formed grains, are what give the Araba formation its name. They also contain different iron oxides and shales. Highly pure sandstone with conglomeratic intercalations makes up the Naqus Formation. The Araba Formation's type site is in the SW Sinai's Gebel Araba, where it reaches a thickness of roughly 25 m (Gomaa et al. 2021).

### Theoretical calculations

We prepared synthetic shale sand mixtures with varying concentrations of shale and saturations. The sand content was varied from 0 to 80% in increments of  $\sim 10\%$ , and the saturation was varied from 0 (dry) to 100% in increments of  $\sim 20\%$ . The electrical conductivity of each mixture was measured using LCR Hitester Impedance-Analyzer (Fig. 2b).

Over forty electrical examinations were done (and we select some cases for this paper) to show the electrical properties using the Hioki 3522-50 LCR Hitester Impedance-Analyzer. The edges of the specimens were handled to be parallel (Shaltout et al. 2012; Al-Sharif and Al-Saleh 2017). The electrical characteristics were evaluated with non-polarizing electrodes ( $\text{Cu}/\text{CuSO}_4$ ) at ambient temperature ( $\sim 25$  °C), with a relative humidity of the atmosphere of  $\sim 64$  g/m<sup>3</sup>, the frequency varies from  $5 \times 10^{-4}$  Hz to 100 kHz. The voltage used was 1 V (Gomaa 2009). In order to determine the electrical characteristics (conductivity, relationships between mixtures) only eight curves were selected. The porosity of sand is on the order of 20 percent; all samples have been compressed at the same pressure.



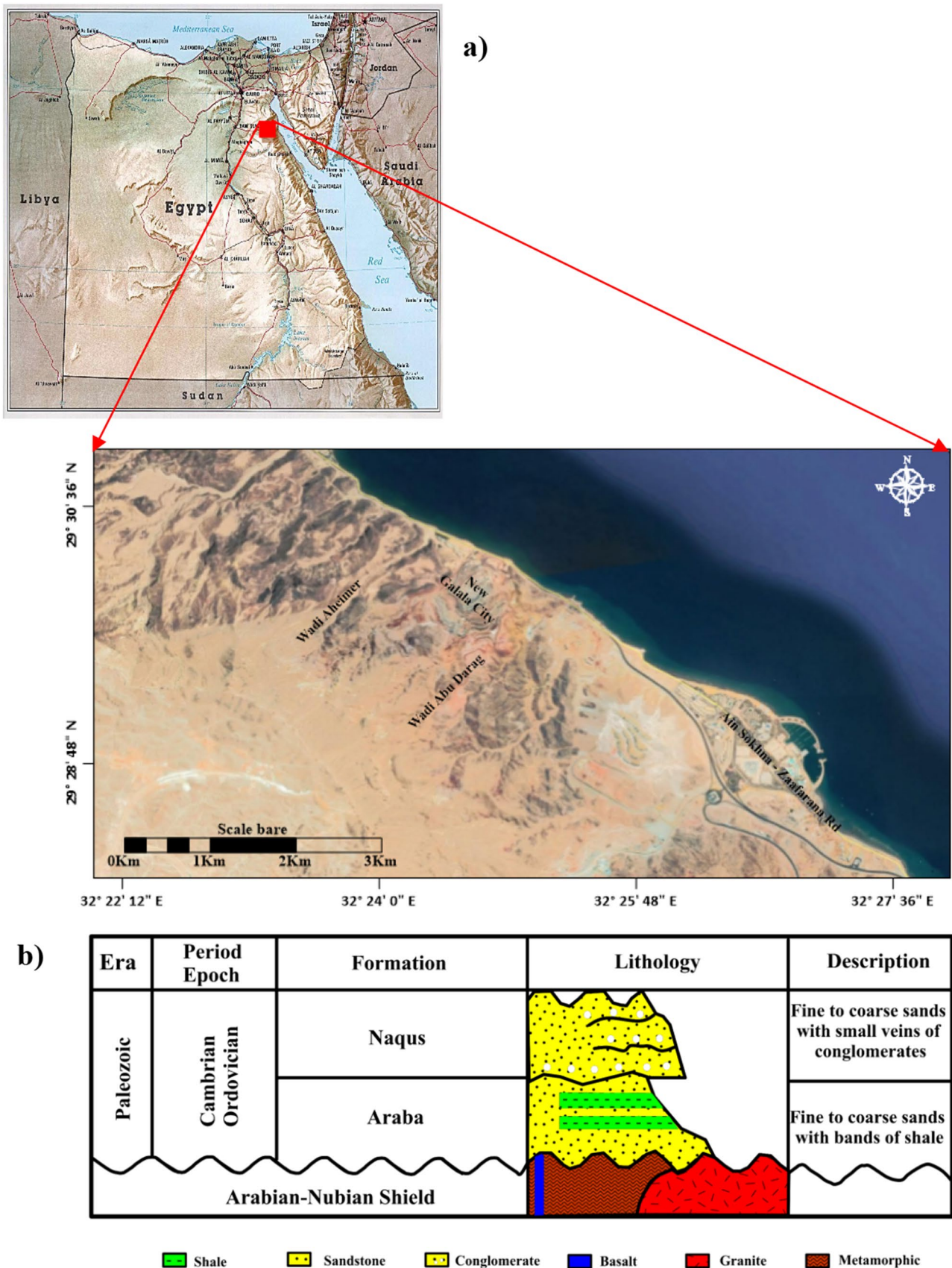
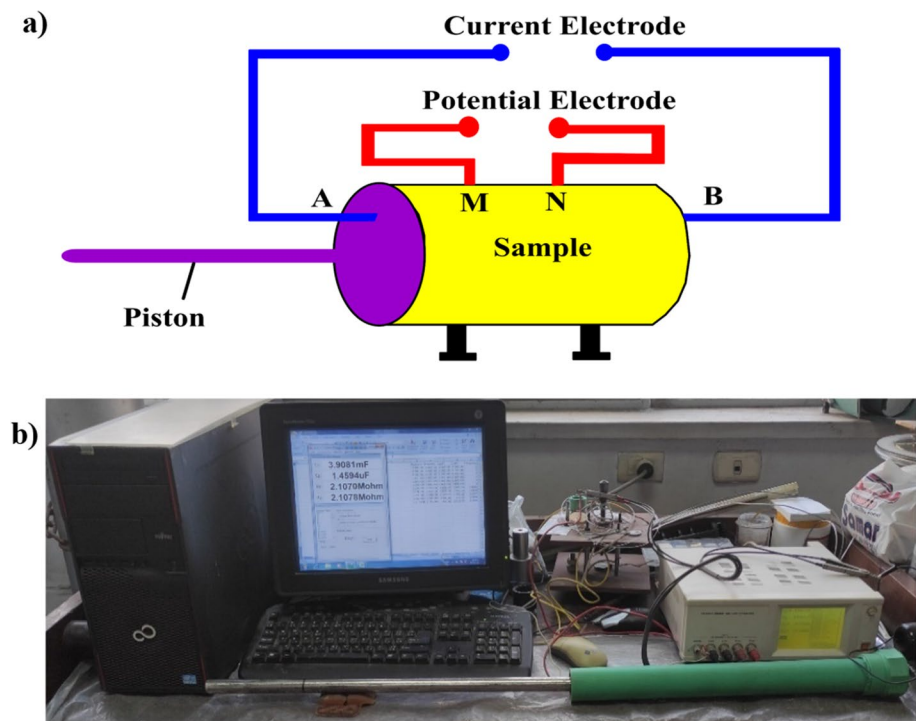


Fig. 1 a A map of Gebel El-Galala, the study area. b Gebel El-Galala's general stratigraphic column

**Fig. 2** a A sketch of how the four-electrode device works. b The real picture of the electrode system with the electrical instrument



Samples were examined by measuring their electrical properties in either a series or parallel configuration. The measurable factors were performed using parallel capacitance and conductance ( $C_p$  and  $G_p$ ) and series impedance  $Z$  at different frequencies. The complex relative dielectric constant is  $\epsilon^* = \epsilon' - i\epsilon''$ , where,  $\epsilon' = C_p d / \epsilon_0 A = C_p / C_0$ , is the real part of the complex relative dielectric constant (permittivity) before correcting the imaginary part of complex relative dielectric constant is  $\epsilon'' = G_p d / \omega \epsilon_0 A$ , where  $A$  is the cross-sectional area of the sample,  $d$  is the sample thickness,  $\epsilon_0 = 8.85 \times 10^{-12}$  F/m is relative permittivity, and  $\omega$  is the angular frequency,  $C_0 = (A/d)\epsilon_0$  is the geometrical capacitance,  $\sigma' = G_p d / A = \epsilon'' \omega \epsilon_0$  is the real conductivity (Gomaa and Alikaj 2009). The real and imaginary dielectric may be written as  $G_p = 1/R_p$  is parallel conductance (Shaltout et al. 2012).

In order to effectively carry out dielectric spectroscopy, an alternating electric field is required. The relative permittivity or dielectric constant is a complex frequency-dependent parameter. Detailed information on the material's properties is provided. The imaginary part ( $\epsilon''$ ) corresponds to energy storage and the real part ( $\epsilon'$ ) corresponds to energy loss of the material. There are four basic polarization mechanisms (Interface, electronic, atomic, and orientation polarization). Every single one of these mechanisms uses a characteristic constant to bypass a particular frequency range (Saltas et al. 2007).

The effects of electrode polarization on electrolyte conductivities were perhaps discovered by Kohlrausch and Holborn (1898). These effects can be mitigated by using non-polarizing electrodes and then lowering the electrode impedance of the surface by orders of magnitude (Warburg 1899 and 1901). They found that the surface electrode impedance includes a non-real part.

The electrode polarization phenomenon, which is based on diffusion phenomena, is originally developed by Warburg impedance. The capacitance  $C_p$  and resistance  $R_p$  of the electrode surface-polarization are proportional to  $f^{-0.5}$ , where  $f$  is the frequency and the impedance has a frequency independent phase angle of  $45^\circ$ . The Warburg impedance law (Fricke 1932) are  $C_p \sim f^{-m}$ ;  $R_p \sim f^{-(1-m)}$  and  $\delta = m\pi/2$ , where  $\delta$  is the phase angle defined by  $\tan\delta = R_p \omega C_p$ . As the frequency increases, the constant  $m$  increases from 0.3 to 0.5. The relation between  $R_p$  and  $C_p$  are the Kramers–Kronig relations (1926). The link between the real and imaginary components of a complex function is described by the Kramers–Kronig relations, which are mathematical equations. If the slopes deviate from these relations, the system under study may not be in equilibrium or may be affected by other factors that are not being taken into consideration.

Frequency domain injecting an alternating current (AC) between two electrodes in contact with the sample material is the basis for SIP measurements. By measuring the electrical potential across a pair of electrodes in the sample,

the phase shift ( $\varphi$ ) and amplitude ( $|\rho|$ ) of the received AC potential in relation to the injected current can be determined. The frequency-domain complex conductivity is  $\sigma^* = \frac{1}{|\rho|} e^{-i\varphi} = \sigma' + i\sigma''$ , where  $\sigma''$  is the out-of-phase and  $\sigma'$  is the in-phase of the complex conductivity ( $|\rho| = \rho * \frac{A}{d}$ ). The complex impedance or admittance ( $Z^*(\omega) = \frac{\rho^*(\omega)l}{A}$ , and  $Y^*(\omega) = \frac{\sigma^*(\omega)A}{l}$ ) can be replaced by resistivity or conductivity (Scott, 2003). The phase angle is ( $\tan\varphi = -\frac{\sigma''}{\sigma'}$ ). This loss angle is ( $\delta = \frac{\pi}{2} - \varphi$ ,  $\tan\delta = \frac{\epsilon''}{\epsilon'}$ ).

### Experimental measuring procedures

First, as seen in Fig. 2, we create our own electrode setup. To minimize the induction of electrical current, the cylindrical tube has been constructed of high-quality plastic. Next, copper (a high-quality electrode) serves as both the potential and current electrode, and the piston that drives it was made of strong-arm steel to withstand high pressure on the electrode system (and the friable sample components).

The studied samples have been collected from Araba formation of El-Galala area, Cairo, Egypt. The location of the shale is  $29^\circ 28' 3.918''$  N and  $32^\circ 27' 10.8108''$  E, whereas the location of the sand is  $29^\circ 30' 20.502''$  N and  $32^\circ 24' 13.284''$  E. Figure 1 depicts the locations of these samples, which were taken from Paleozoic and Cambrian-Ordovician outcropping formations. The samples were collected, dried for one day at a temperature of  $40^\circ\text{C}$ , sieved with a mesh of grain size (sand size) 0.0625 mm, and subsequently weighed. Sand (clean sieved) was added to the shale in different quantities and the percentage of weight of the additive was calculated as shown in Fig. 3. First, we utilize the sieved pure sand to examine the physical response of the electrical current with different concentrations of sand. Then, we add 10% of sieved clean shale of the total amount of sand. We start with 65.5 g of pure sieved shale, and then add 6.55 g of sand to get the

first sample of 10%. Then, we calculate the sand ratio (Sr) as  $Sr = \frac{S*n}{Sh+(S*n)} * 100$ , where S is the weight in grams of the sand, Sh is the weight in grams of the shale, and n is the number of sand additions. Samples are identified by the amount of sand they include, such as Sh41S, which indicates that the sample contains 41% sand and 59% shale.

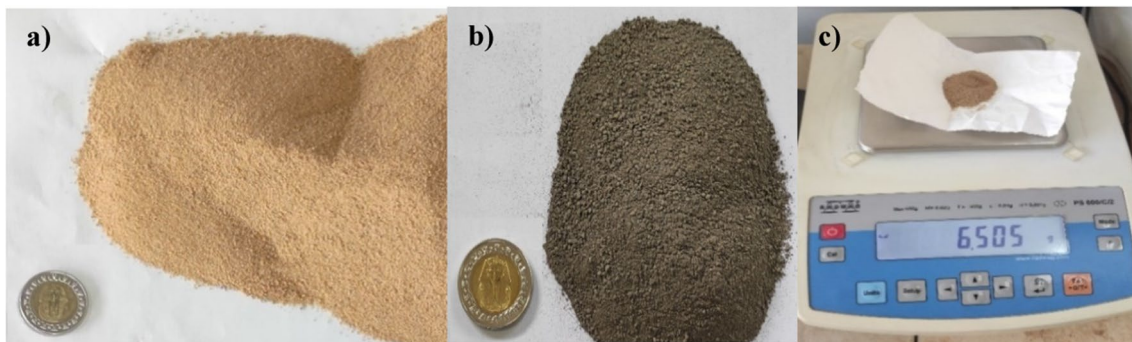
### Dry and wet mixture of sand and shale

The saturation ( $S_w$ ) of the samples was changed from partially to fully saturated by adding a known quantity of water. The electrical characteristics of these samples were measured by the same electrode and impedance analyzer. The samples were placed isolated from the air in a sealed vessel (Desiccator). The effective electrical conductivity in the free pore space, where surface conduction is negligible, is determined by the cross-section, length, and connectivity of the conduction pathways or interconnections at the sample. The following empirical law, for predicting geological water-saturated materials, is shown as  $S_w = \frac{V_w}{V_p}$ , where  $V_w$  and  $V_p$  are the volume of water and pore, respectively.

## Results and discussions

### Effect of increase of shale content

The electrical conductivity of shaly sands is a topic of interest in the oil and gas industry as it provides information for water saturation and evaluation of hydrocarbon-bearing formations. Shale is a sedimentary rock composed predominantly of clay minerals and minute fragments of other minerals, including quartz, feldspar, and mica. Due to the prevalence of these conductive minerals, shale possesses a higher electrical conductivity than sand. When shale is mixed with sand, the resulting mixture (synthetic shale and sand) has a conductivity that is intermediate



**Fig. 3** Sieved samples **a** sand, **b** shale, and **c** weighing instrument



between that of pure sand and pure shale. As the proportion of shale in the mixture increases, so does the electrical conductivity. This is because the conductive minerals in the shale become more dominant in the mixture and contribute more to the overall conductivity. It's worth noting that the specific conductivity of the shale sand mixture can also depend on other factors, such as the size and shape of the shale particles, the moisture content of the mixture, and the presence of other minerals or contaminants (De Lima and Sharma 1991; 1992; De Lima 1995). However, the electrical conductivity of a synthetic shale sand mixture will generally increase with increasing shale content (Gomaa 2008).

The pore water salinity, surface conductivity, and cation-exchange capacity of the rock influence the electrical conductivity of shale-like sediments. Shaly sands' cation-exchange capacity is dependent on the clay minerals present in the rock. Due to the presence of clay minerals and their influence on the cation-exchange capacity of the mixture, it is conceivable that the electrical conductivity of a synthetic shale sand mixture would increase with increasing shale content.

Sand is an insulator or semi-insulator, whereas shale is a semi-conductor or conductor. The conductivity variation as a function of frequency of dry sand, shale, and their mixture (synthetic shale and sand) is shown in Fig. 4. The electrical conductivity reduces across the material as the sand content rises. There are three distinct groups that can be deduced from the electrical response of this compound mixture. Samples Sh77S, Sh78S, and Sh79S correspond to the first category, which exhibits constant DC-conductivity with increasing frequency. DC-conductivity in specimens Sh64S and Sh70S from the second category may show somewhat increased conductivity (at a relatively low frequency). DC-conductivity is not present in pure shale Sh41S samples, which fall into the third category. From these results, we deduce that the DC-conductivity must decrease as the sand content grows. Kramer–Kronig analysis shows that the slopes of our samples fall into two distinct classes, with the first (class 1) spanning 0.14–0.64 and the second (class 1) spanning 0.24–1. The Kramer–Kronig relation does not hold for these gradients. We found that the slopes rise by a factor of 1.1–3.6 when the sand ratio is raised. Based on the amount of shale present, these specimens may be separated into two groups. The first one consists of pure shale, Sh41S, Sh64S, and Sh70S, all of which have a very high shale concentration (very low sand). Sh77S, Sh78S, Sh79S, and pure sand are examples of low shale concentration (high sand) samples.

Therefore, an unexpected conductivity changes between Sh64S and Sh70S as a result of typical abrupt shift from  $2 \times 10^{-6}$  to  $2 \times 10^{-4}$ ; this may be the percolation threshold. The second sample group consists of Sh77S, Sh78S, Sh79S

and pure sand, with relatively high concentration of sand (low shale concentration). This group has a conductivity range of  $10^{-6}$  to  $4 \times 10^{-6}$ , and there is a sudden change (at relatively high frequencies) before an abrupt change in conductivity.

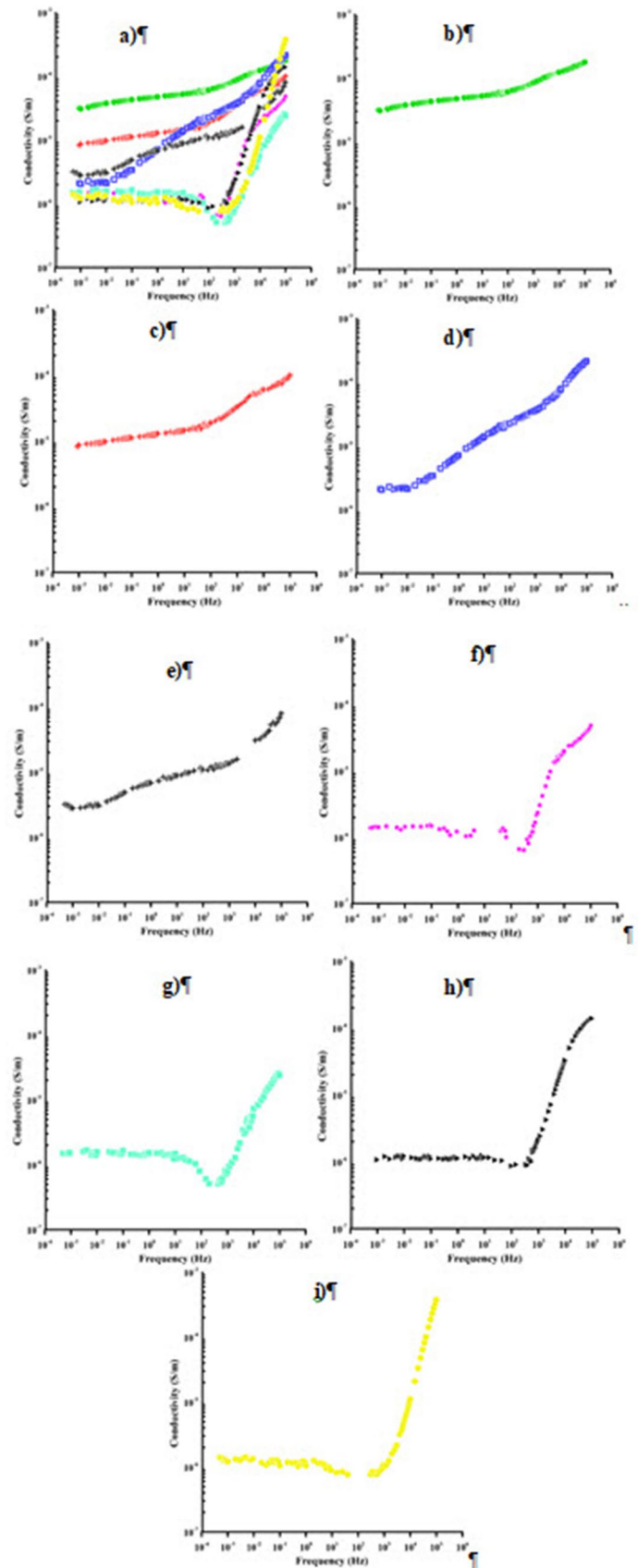
In general, as frequency and concentration of total conductors increase, more continuous conductor connections between minerals and grains begin to occur, leading to increase in conductivity values (Xie and Li 2018; Gomaa 2013). Because the levels of particle activity grow, to higher energy barriers between atoms, conductivity values rise with increasing frequency. These processes change the behavior of the particles from insulator to semiconductor or conductor. There is a sharp increase in conductivity between low and higher conductivity values that reaches a maximum value of conductivity and finally it begins to saturate at this maximum value. Conductivity in SIP measurements may give indication to distinguish between the conducting and non-conducting materials below 10 kHz.

Figure 5 shows how the dielectric constants of the mixture (synthetic shale and sand) changes with frequency for dry samples. Dry specimens are a combination of the material and air, consequently their dielectric constant is determined by both of these factors. The degree to which a material is able to retain electrical energy in an electric field is quantified by its dielectric constant. For dry samples, the dielectric constant of a synthetic shale and sand combination varies with frequency. Several factors, including a material's mineral and fluid content, temperature, pressure, and the geometry of its solid components and pore spaces, can affect its dielectric properties. The dielectric properties of shale are highly sensitive to fluctuations in its clay concentration.

As an indication of frequency, the dielectric constant of the compound varies. Therefore, components like water saturation, pore fluid salinity, and the composition of the mixture influence the specific behavior of the dielectric constant with frequency. Polymeric dielectrics used in energy storage capacitors, microelectronic devices, and high-voltage insulation all rely significantly on the frequency-dependent dielectric constant.

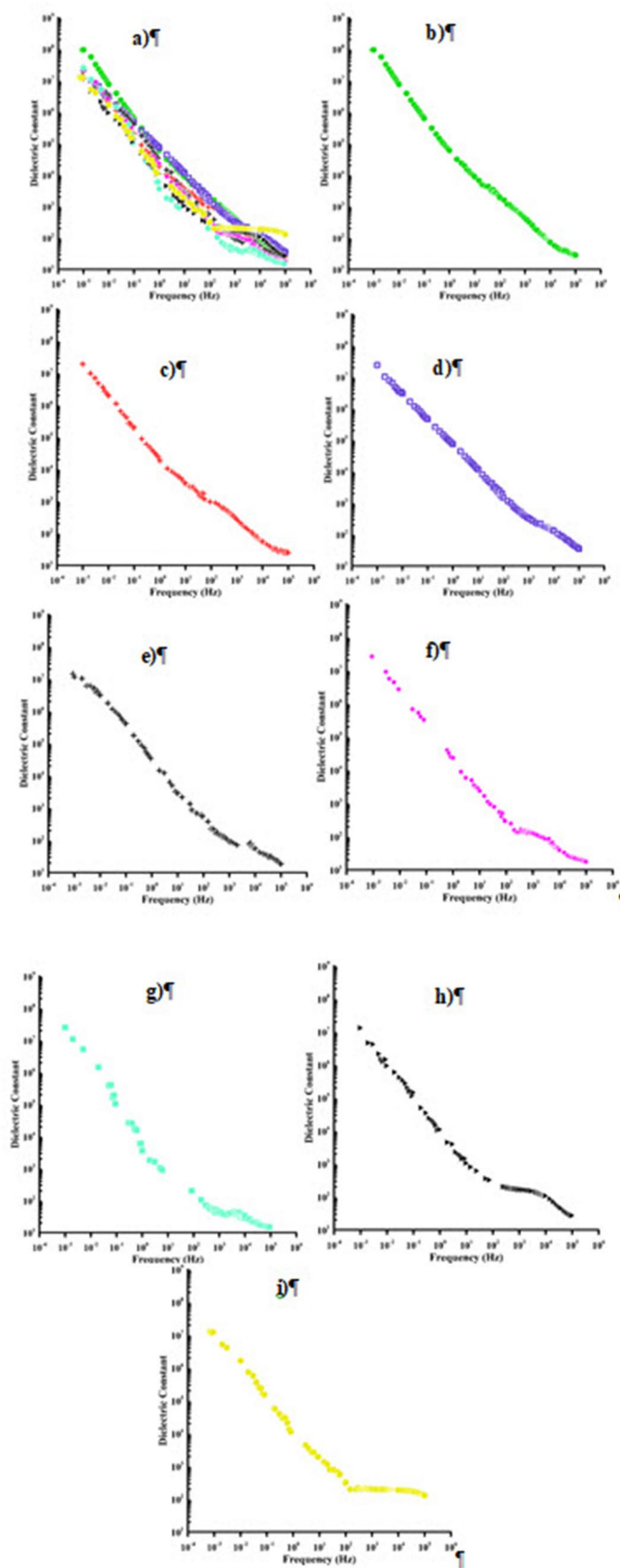
As frequency increases, the dielectric constant drops. Frequency dispersion refers to the phenomenon in which the dielectric constant of a material varies as a function of frequency. The dielectric constant varies because it depends on how well a material can store and release electrical energy in response to an applied electric field. The electric field induces polarization at low frequencies, leading to charge separation and accumulation at the grain surfaces. The dielectric constant rises as a result of this. However, the polarization response weakens as the frequency increases because there is less time for the charges to separate and accumulate. There's also the possibility that the charges won't have time

**Fig. 4** Shows how the conductivity changes with the frequency of dry (Green filled circle with dashes) pure shale, (Yellow filled circle with dots) pure sand, (Red filled plus) Sh41S, (Blue square) Sh64S, (Black filled plus) Sh70S, (Pink filled star) Sh77S, (Light green filled square) Sh78S, and (Black filled right faced triangle) Sh79S. How the conductivity changes with the frequency of dry (Green filled circle with dashes) pure shale, (Yellow filled circle with dots) pure sand, (Red filled plus) Sh41S, (Blue square) Sh64S, (Black filled plus) Sh70S, (Pink filled star) Sh77S, (Light green filled square) Sh78S, and (Black filled right faced triangle) Sh79S

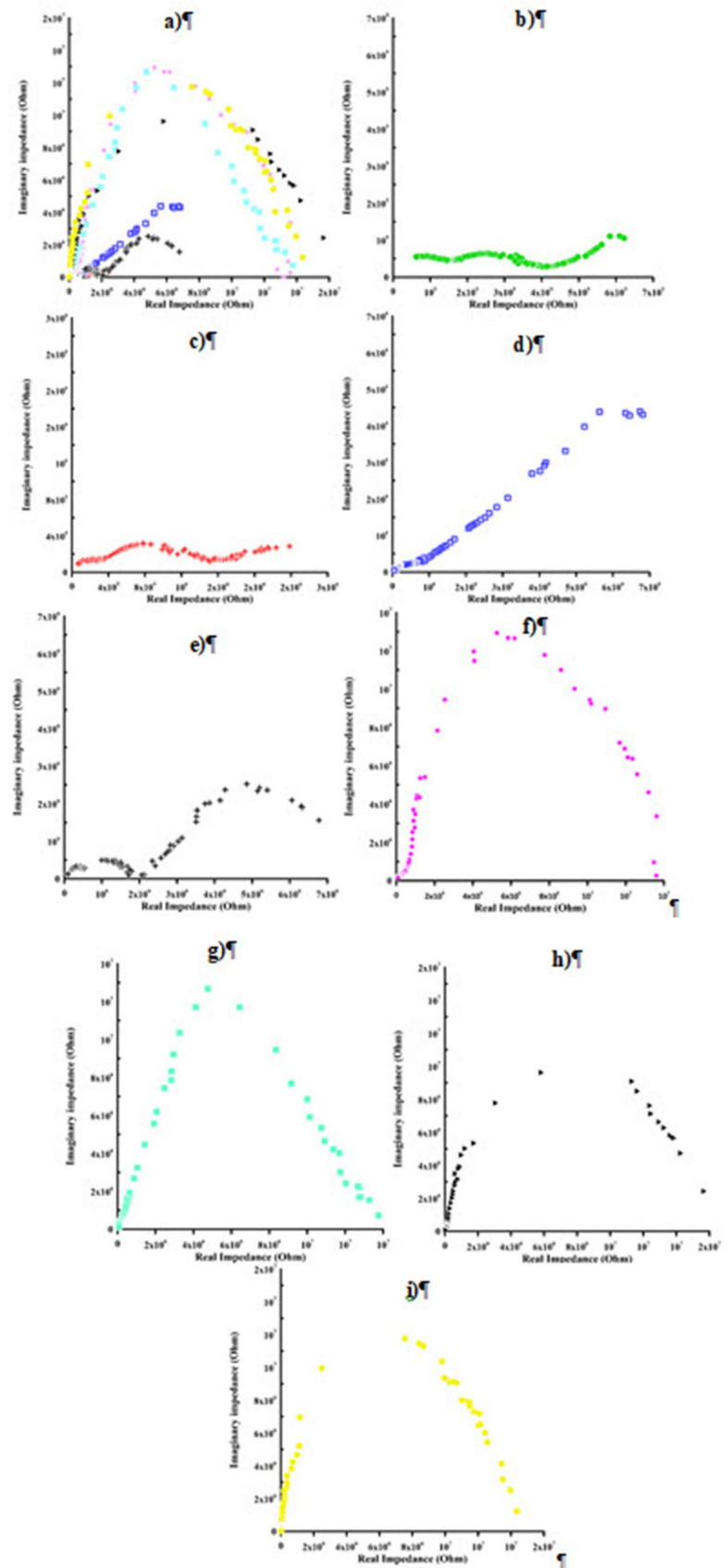




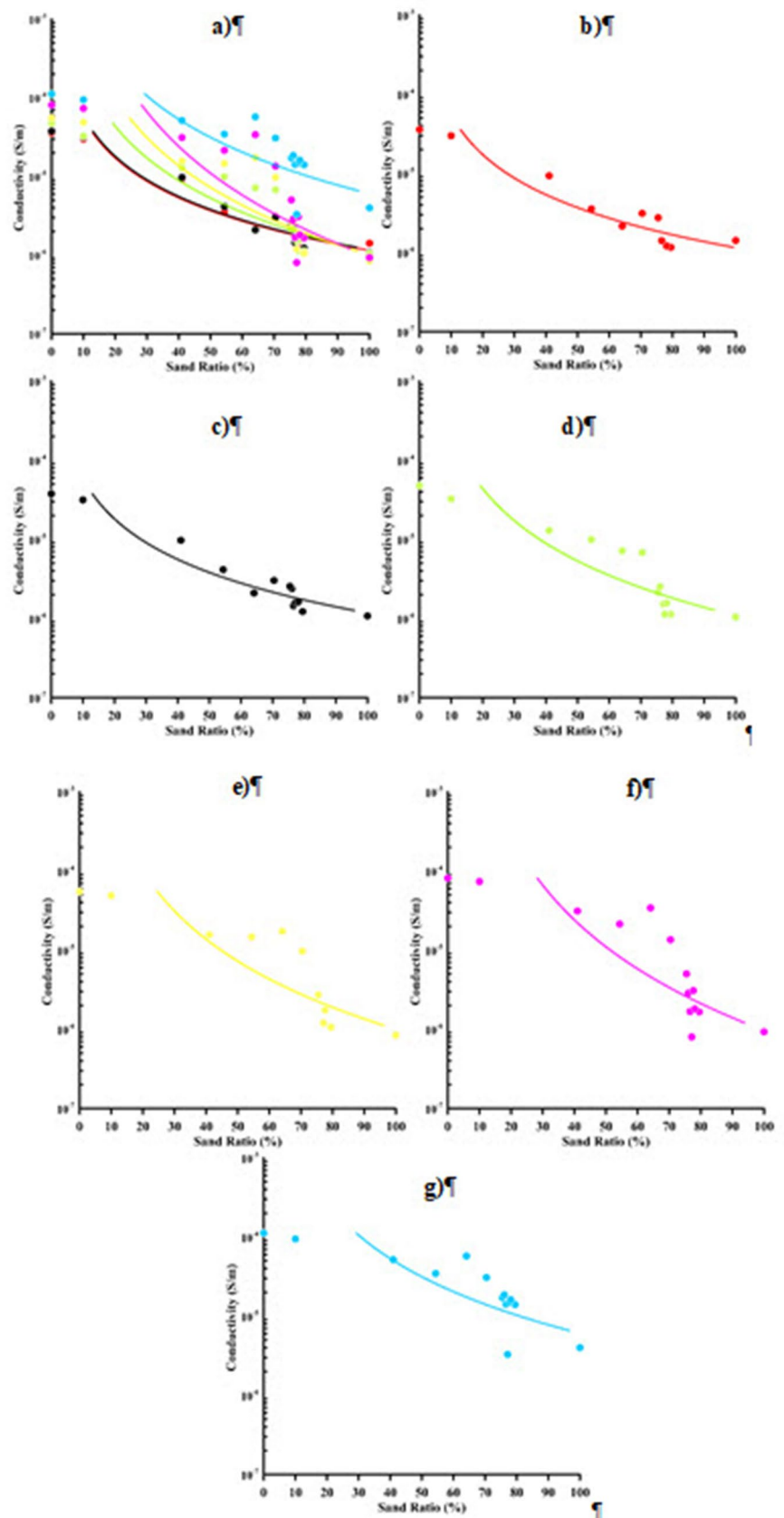
**Fig. 5** Shows how the dielectric constant changes with the frequency of dry (Green filled circle with dashes) pure shale, (Yellow filled circle with dots) pure sand, (Red filled plus) Sh41S, (Blue square) Sh64S, (Black filled plus) Sh70S, (Pink filled star) Sh77S, (Light green filled square) Sh78S, and (Black filled right faced triangle) Sh79S. How the dielectric constant changes with the frequency of dry (Green filled circle with dashes) pure shale, (Yellow filled circle with dots) pure sand, (Red filled plus) Sh41S, (Blue square) Sh64S, (Black filled plus) Sh70S, (Pink filled star) Sh77S, (Light green filled square) Sh78S, and (Black filled right faced triangle) Sh79S



**Fig. 6** The Argand (Impedance) plane for dry (Green filled circle with dashes) pure shale, (Yellow filled circle with dots) pure sand, (Red filled plus) Sh41S, (Blue square) Sh64S, (Black filled plus) Sh70S, (Pink filled star) Sh77S, (Light green filled square) Sh78S, and (Black filled right faced triangle) Sh79S. The Argand (Impedance) plane for dry (Green filled circle with dashes) pure shale, (Yellow filled circle with dots) pure sand, (Red filled plus) Sh41S, (Blue square) Sh64S, (Black filled plus) Sh70S, (Pink filled star) Sh77S, (Light green filled square) Sh78S, and (Black filled right faced triangle) Sh79S



**Fig. 7** Displays the best-fitting curves for conductivity as a function of frequency for sand saturation in shale **a** at different frequencies **b** (Red filled circle) 5 mHz, **c** (Black filled circle) 10 mHz, **d** (Light green filled circle) 1 Hz, **e** (Yellow filled circle) 25 Hz, **f** (Pink filled circle) 700 Hz, and **g** (Sky blue filled circle) 5 kHz. Displays the best-fitting curves for conductivity as a function of frequency for sand saturation in shale **a** at different frequencies **b** (Red filled circle) 5 mHz, **c** (Black filled circle) 10 mHz, **d** (Light green filled circle) 1 Hz, **e** (Yellow filled circle) 25 Hz, **f** (Pink filled circle) 700 Hz, and **g** (Sky blue filled circle) 5 kHz



**Fig. 8** Demonstrates the frequency-dependent conductivity variation for dry and thoroughly saturated sand [(Yellow filled circle with dots) dry sand, (Red filled circle) 13%, (Black filled circle) 27%, (Red filled square) 40%, (Blue filled square) 60%, (Red filled plus) 67%, (Blue filled plus) 73%, (Black filled square) 87%, (Black filled plus) 93%, and (blue filled circle) fully saturated]. Demonstrates the frequency-dependent conductivity variation for dry and thoroughly saturated sand [(Yellow filled circle with dots) dry sand, (Red filled circle) 13%, (Black filled circle) 27%, (Red filled square) 40%, (Blue filled square) 60%, (Red filled plus) 67%, (Blue filled plus) 73%, (Black filled square) 87%, (Black filled plus) 93%, and (blue filled circle) fully saturated]

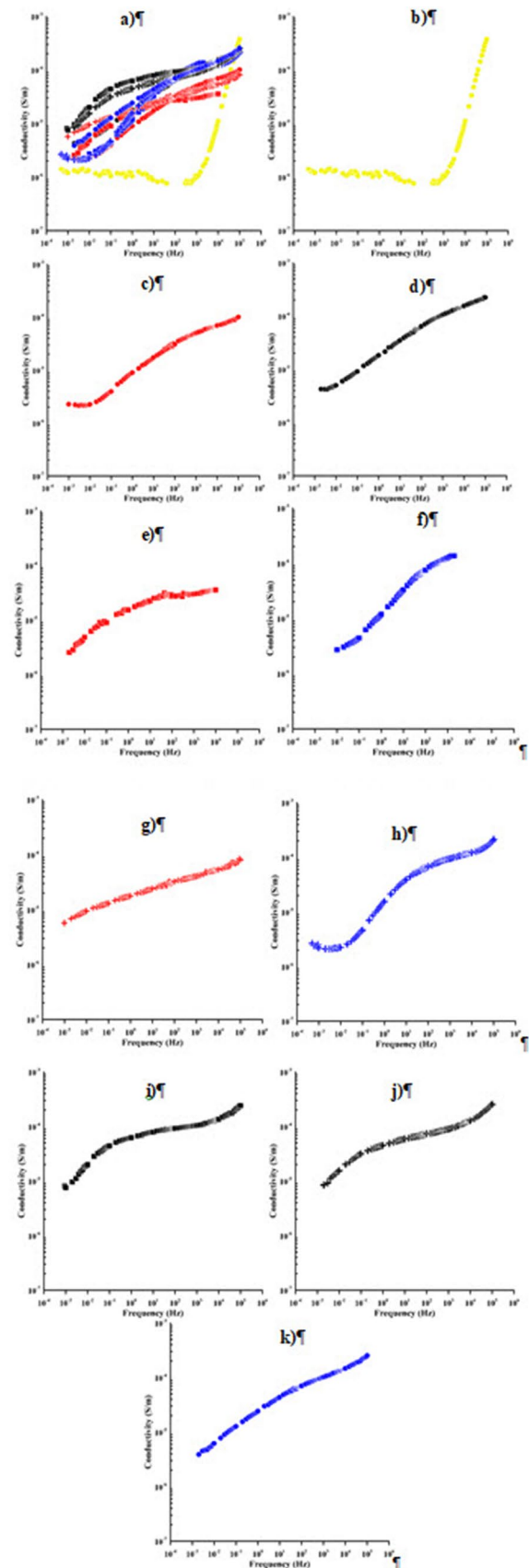
to realign in response to the alternating electric field, resulting in a lower dielectric constant.

The frequency dependence of the dielectric constant is a consequence of the mixture's composition, structure, and texture, as well as the properties of the individual components. In the case of synthetic shale and sand, the dielectric constant may vary differently for each component, and the overall frequency dependence of the mixture will depend on the relative amounts of each component and their distribution within the mixture. When the concentration of conductors in a material increases, the distance between them decreases. This causes the electric field between the conductors to increase, which results in a decrease in the dielectric constant.

The dielectric constant quantifies a material's capacity to absorb and store electric energy. Therefore, the ability of a substance to store electrical energy is inversely proportional to its dielectric constant. Sample Sh78S has a slope of +1.5, which deviates from the Kramers–Kronig relations, which are typically in the -0.6 to -0.98 range.

Due to an increase in the energy of charged particles and a decrease in the size of gaps between grains, the dielectric constant of a material drops with an increase in frequency. In contrast, the dielectric constant rises as there is less space between the grains. High values of the dielectric constant are inspired by the short insulating gaps between semi-conducting clusters or grains. High dielectric constant at low frequencies may explain why grains in samples are being sorted more thoroughly than usual. As the frequency increases, the dielectric constant and loss factors drop. According to research (Gomaa et al. 2015a, b), the dielectric constant rises with humidity or temperature but falls with frequency.

A sample's dielectric constant corresponds to alterations in the relative abundance of insulating and conducting elements. Up to the percolation threshold, the conductor concentration increases while the frequency causes the dielectric constant to fall. When an electric field is generated, electrons are free to move between two locations; this results in an additional reduction in the dielectric constant. Dielectric dispersion is very important for the applications of dielectric materials and the analysis of their properties. In mineral oil-based nano-fluids, the dielectric constant



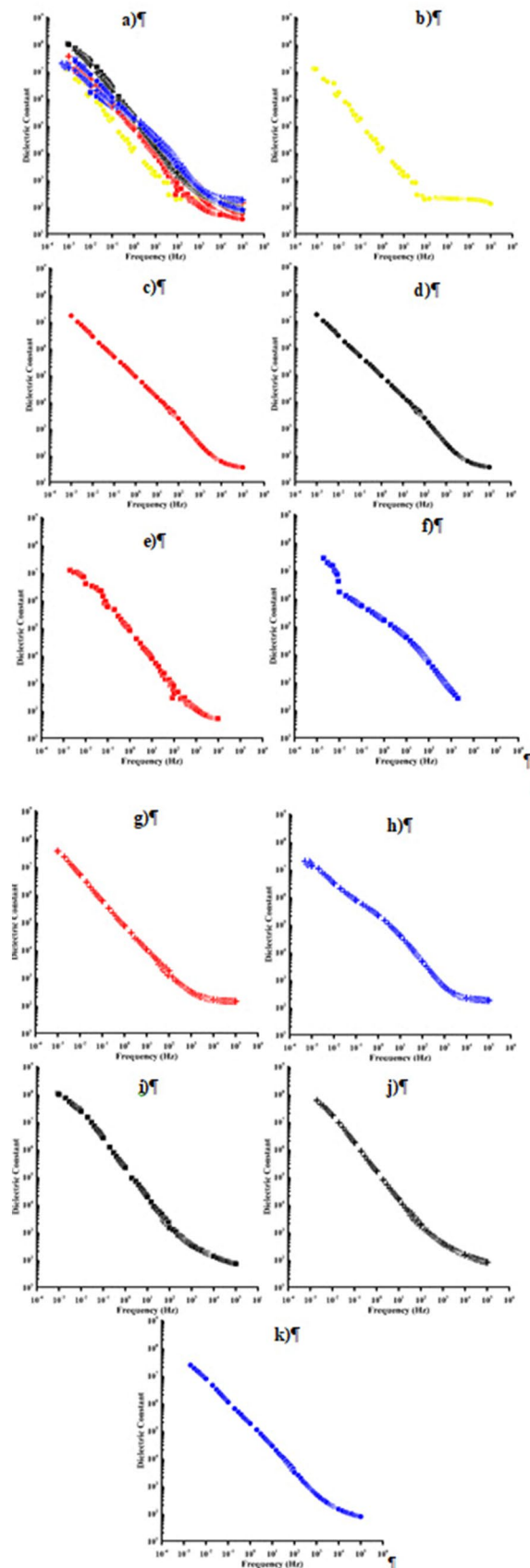


**Fig. 9** Contrasts the frequency dependence of the dielectric constant under conditions that are unsaturated, moderately saturated, and fully saturated [(Yellow filled circle with dots) dry sand, (Red filled circle) 13%, (Black filled circle) 27%, (Red filled square) 40%, (Blue filled square) 60%, (Red filled plus) 67%, (Blue filled plus) 73%, (Black filled square) 87%, (Black filled plus) 93%, and (blue filled circle) fully saturated]. Contrasts the frequency dependence of the dielectric constant under conditions that are unsaturated, moderately saturated, and fully saturated [(Yellow filled circle with dots) dry sand, (Red filled circle) 13%, (Black filled circle) 27%, (Red filled square) 40%, (Blue filled square) 60%, (Red filled plus) 67%, (Blue filled plus) 73%, (Black filled square) 87%, (Black filled plus) 93%, and (blue filled circle) fully saturated]

varies due to changes in insulator and conducting (mineral) concentrations. When nanoparticles are added, this variance may change the breakdown strength and produce different outcomes for the mineral oils' dielectric dissipation (Gomaa et al. 2018).

Figure 6 shows the difference between the in-phase and out-of-phase (Real and imaginary) impedance of samples with different sand shale mixture percentages. The study analyzed the complex resistivity of pure sand, pure shale and shaly sand samples dry and with different saturations. The results suggest that changes in impedance response are consistent across different shale samples and can be analyzed using rock physics models. All of the samples' measured impedance values fit within the shape of a semicircle with an arc (or line) attached to it. As the total number of conductor conduction pathways increases (as it does with high concentrations of conductor minerals), the arc contracts (which demonstrates low impedance) and creates a half circle. When the number of total conductor conduction channels between electrodes is decreased, the in-phase and out-of-phase impedance of samples increases. The Argand plot displays an arc that should be a component of the semicircle when the concentration of conductors is small (the sample is virtually an insulator). As the concentration of conductors increases, this arc converts to a part of a semicircle. For larger concentrations of conductors, this arc may be constrained to a semicircle (Grant, 1958).

Figure 6 shows an arc attached to a depressed semicircle (or semicircle). There may be a reduction in the effective impedance if the number of continuous conductor paths between electrodes increases. This means that changing shale ratio and their texture (porosity, concentration grain size and grain shape) will change the resultant Argand plot. A material's electrical properties can be investigated with the use of the impedance plane. In the case of shale and sand content, we can observe a decrease in impedance with increasing shale content compared to sand content. This is likely due to the fact that shale is a better conductor than sand, meaning that it allows electrical current to flow more easily. As a result, the impedance of a material containing more shale will be lower than a material containing more



**Fig. 10** Demonstrates the Impedance plane for dry and saturated sand [(Yellow filled circle with dots) dry sand, (Red filled circle) 13%, (Black filled circle) 27%, (Red filled square) 40%, (Blue filled square) 60%, (Red filled plus) 67%, (Blue filled plus) 73%, (Black filled square) 87%, (Black filled plus) 93%, and (blue filled circle) fully saturated]. Demonstrates the Impedance plane for dry and saturated sand [(Yellow filled circle with dots) dry sand, (Red filled circle) 13%, (Black filled circle) 27%, (Red filled square) 40%, (Blue filled square) 60%, (Red filled plus) 67%, (Blue filled plus) 73%, (Black filled square) 87%, (Black filled plus) 93%, and (blue filled circle) fully saturated]

sand. There are several potential uses for this data, including oil and gas development. The preparation of samples for measurement starts with pure shale, and then we try to increase the concentration of shale on steps.

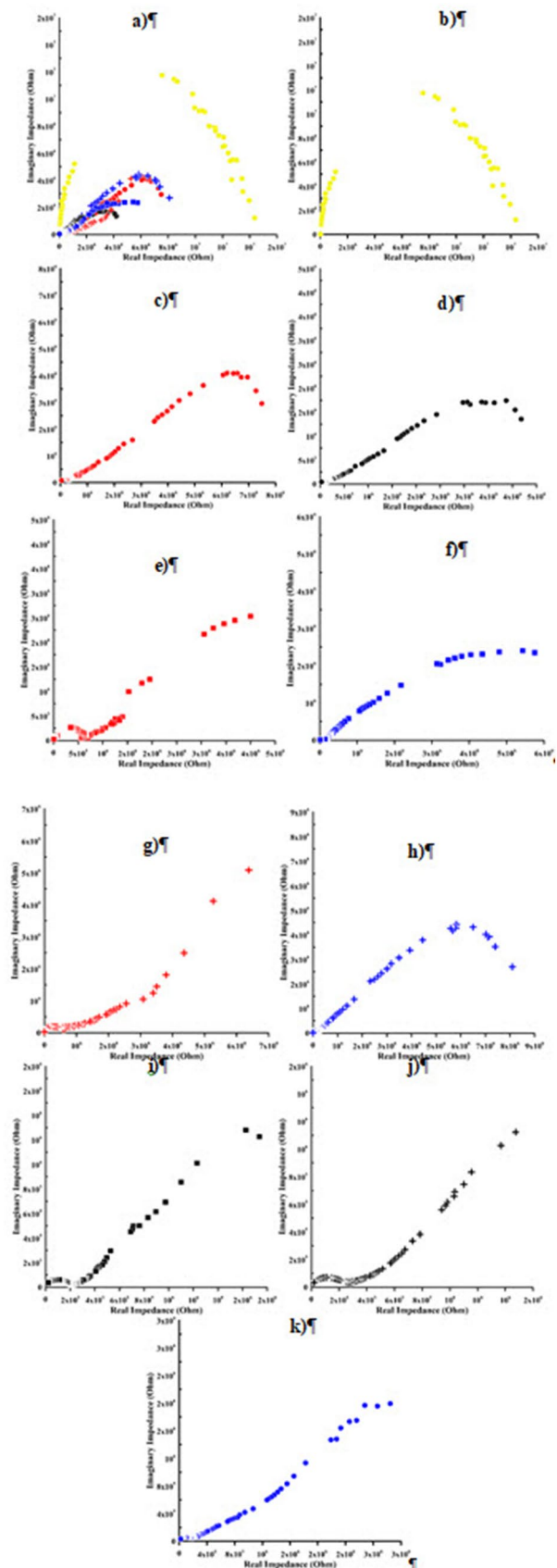
Curves in Fig. 6 may be divided into three categories by curve form. The first category consists of two semicircle curves with multi-relaxation times. The relaxation time of pure shale, Sh41S, and Sh70S is the time required by a static electrical field to generate an equilibrium ionic distribution in the Stern layer covering a grain of a particular diameter. The second group consists of skewed arc curves with one relaxation time as shown in sample Sh64S. The third group that has one semicircle includes curves which, as shown in samples pure sand, Sh77S, Sh78S and Sh79S.

In practice, the appearance of a semicircle in the Argand plot indicates that the conductivity can convey both DC and AC conductor paths. The presence of simply one arc in the impedance plane indicates poor distribution of total conductor pathways. A sample with two distinct conduction processes, alternating current (AC) and direct current (DC), is indicated by an arc interconnecting a semicircle on the impedance plane (Gomaa and Abou El-Anwar 2019).

Figure 7 displays the curves for conductivity as a function of frequency for sand saturation in shale (a) at 5 mHz, 10 mHz, 1 Hz, 25 Hz, 700 Hz, and 5 kHz. The electrical conductivity of shaly sand is nonlinearly dependent on pore fluid conductivity. The electrical conductivity of shaly sands is affected by electrolyte conductivity, porosity, and clay properties. It is clear from the curves that the conductivity is decaying exponentially with the increase of water saturations for all frequencies. Also, at a certain frequency, the decay of frequency with the increase of water saturations is sharp at low frequencies and become gentler as the frequency increase.

**Effect of saturation of water**

To figure out the impact of water on electrical properties, researchers examined the conductivity of synthetic impure sand samples. Sand grains in the sample range in size from



0.09 to 1.7 mm, while shale grains are on the order of  $\sim 60$   $\mu\text{m}$ . At room temperature, the sandstone samples act as an insulator. The conductivity drops to the order of  $\sim 10^{-10}$  S/m when dried. However, when either a small or large amount of water is added to the samples, the conductivity rises. While having the same amounts of water, clay, and sand, specimens with different textures might exhibit completely distinct electrical behaviors.

The second factor that we try to speculate its effect is the increase of water saturation to dry sand sample. We start to study the effect of dry, partially, and fully saturated sand samples by adding definite water quantities. Values regarding conductivity, dielectric permittivity, and impedance all changed quickly at low saturations but slowed down significantly at high saturations.

At a certain frequency, there is an abrupt change in conductivity ( $\sim 10^3$  Hz) and measurements of conductivity ranging from  $10^{-6}$  to  $10^{-5}$  S/m. Because the number of continuous paths in the conducting medium (water) increases as saturation and frequency increases, then the impedances decrease. When comparing low water saturation to dry, there is a significant increase in conductivity magnitude. On the other hand, for moderate water saturation ( $\sim 13$  to 70%), the conductivity rises slightly with increasing water saturation. Finally, measurements of conductivity starts to be stable with additions of water saturation (at very high saturation levels) approaching its highest values.

A semicircle, or a depressed semicircle, can be observed on the impedance plane. In general, as saturation increases, higher frequencies will be observed at the peak (in which the semicircle intersects the line). The fact that higher water saturation adds some conducting channels to conductivity measurements may account for the higher peak frequency observed in the impedance values as their higher semicircles increase in frequency. The increasing rate of saturation is connected to the peak frequency, which is almost inversely proportional to the time constant. When comparing dry rocks to partially or fully saturated rocks, the SIP values may provide some insight. This is apparent between  $10^4$  Hz and  $10^{-2}$  Hz for conductivity and 100 Hz and 10 kHz for the dielectric constant.

Figure 8 shows the variation of conductivity as a function of frequency for dry, partially, and fully water saturated sand. There is a clear difference between the dry samples and the partially or fully saturated samples. DC conductivity appears in dry sand and disappears with the increased amount of water.

For dry sand sample, it is noticed that there is an abrupt change in conductivity with frequency ( $\sim 10^3$  Hz) and the conductivity value increases from  $10^{-6}$  to  $10^{-5}$  S/m with frequency increase. With increasing saturation of water, there is a slight increase in slopes (especially for high frequencies),

ranging from 0.1 to 0.5. However, at higher frequencies, the cycle period is shorter than the time it takes for the charges to polarize, therefore movable surface charges contribute more to conductivity measurements than they do at lower frequencies.

An important topic in geophysics that is essential to the study of soil and groundwater properties is the frequency-dependent conductivity variations for dry, partially, and fully water-saturated shaly sand mixture. In general, the conductivity of sand increases with increasing water content due to the increased availability of charged particles (ions) that can conduct electricity. However, the relationship between conductivity and frequency is not straightforward and can depend on various factors, such as the size and shape of the sand particles, the type and concentration of dissolved ions in the water, and the temperature and pressure conditions. For dry sand, the conductivity is typically low and relatively constant across a wide range of frequencies. This is because dry sand contains few conductive ions and has a low water content, which limits the ability of ions to move and conduct electricity.

For partially water-saturated sand, the conductivity increases with increasing frequency due to the polarization of the sand–water interface. At high frequencies, the polarization becomes less effective and the conductivity begins to level off. For fully water-saturated sand, the conductivity is high and relatively constant across a wide range of frequencies. This is because the sand is saturated with water and contains a high concentration of conductive ions, which can easily move and conduct electricity. Therefore, it is important to conduct thorough studies and experiments to accurately characterize the conductivity characteristics of different types of sand under different conditions. The ability of a material to conduct electricity depends on how easily electrons can move through it. Soil conductivity increases with either a higher saturation or a higher dry density. Sand's ac conductivity as a function of frequency rises as the frequency increases.

Figure 9 compares the frequency dependence of the dielectric constant for unsaturated, moderately saturated, and fully saturated conditions. Dry materials possess a dielectric constant that varies with frequency and can reach values as high as  $10^7$ . Over the observed frequency range, the relative dielectric permittivity of dry rock decreases. When water is present in a rock sample, however, it has a significantly challenging effect on the sample's electrical characteristics. Salinity could have a significant impact on the electrical characteristics. Saturation affects the dielectric constant of materials. The saturation effect causes a decrease in the dielectric constant. Bulk dielectric-constant values rise with increasing water saturation due to water's more powerful dielectric constant. The dielectric constant in the sample

follows a power law with frequency ( $\epsilon/\alpha f^n$ ), with a very small variation of the exponent  $n$ , due to the dispersion of pore throats and grain sizes (Gomaa and Elsayed, 2009). The exponent for fully saturation is  $n \approx -0.73$  while the exponent for low saturation is  $n \approx -0.65$ . The behavior of power-law is consistent with Jonscher's observation (Jonscher, 1977 and 1999) and suggestion of a universal power-law. Dielectric constant in SIP measurements may give indication to distinguish the dry and partially or fully saturated rocks in the present frequency range.

Figure 10 shows the change in the impedance plane according to the water saturation of sand. These diagrams have the shape of semicircle in dry, partial and fully saturated sand. The impedance plane of partially saturated materials is affected by both the material characteristics and the electrode contact impedance.

## Conclusion

Shale mixture electrical properties help explain reservoir rock behavior. SIP non-destructively characterizes aquifers. We investigate how shale and saturation affect the electrical conductivity of sand-based synthetic materials. At ambient temperature, the testing covered 1 mHz to 100 kHz. Shale concentration and saturation have never been tested on the A C electrical properties of a synthetic shale sand mixture. We study conductor–insulator combination electrical properties. Saturation and shale concentration increased electrical conductivity and dielectric constant. Shale minerals and water ionization increase conductivity. The dielectric constant drops from low saturation values after reaching the percolation threshold. In the impedance plane, increasing sand concentration decreases impedance. Saturation raises peak frequency. Shale makes power transmission easier. Several samples deviate from Kramer–Kronig. Many variables affect electrical characteristics. The mixtures have high conductivity and dielectric constant at lower frequencies. Saturated samples have higher conductivity than dry samples and low water saturations. Moderate water saturation (13–70%) increases conductivity gently. Finally, high saturation levels saturate conductivity. These findings illuminate reservoir rock electrical properties and can improve oil and gas extraction. SIP is a promising rock texture characterizer for sample component contents. Further work is needed as a future work to study the details of the others factors affecting electrical properties.

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**Data availability** All data generated or analyzed during this study are included in this published article.

**Materials availability** All of the material is owned by the authors and/or no permissions are required.

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