



# Grain size effect on electrical properties of dry friable sand

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**Abstract** The current experiment is designed to look into the effect of pore size dispersion on the electrical properties of some friable sand samples at frequencies ranging from  $10^{-4}$  to 100 kHz. A large amount of friable sand was sieved. Individual grain sizes were collected and compacted under appropriate pressure to create a sample that would later be measured electrically. The grain size dispersion covers a range from 5 mm up to 56  $\mu$ m (5 mm, 3.15 mm, 2.5 mm, 1.6 mm, 1 mm, 0.75 mm, 0.5 mm, 0.63 mm, 0.4 mm, 0.25 mm, and 0.056 mm). The samples were compressed into a disk of appropriate size. The observed changes will be due solely to grain size dispersion. The electrical properties of the samples were able to recognize different grain size effects. The main dominant and controlling factor on the electrical properties of the specimens is grain size, in addition to texture or surface roughness. The electrical properties of curves revealed that the conductivity and dielectric constant increase as grain size decreases. Conductivity increases due to an increase in conducting clusters between grains, i.e., the formation of apparently semi-conducting clusters between grains. The decrease in porosity between grain sizes, i.e., the volume of air between grains, has resulted in an increase in the dielectric constant. This is accepted logically because grain size decreases the number of pore voids or throats between grains. In addition, as grain size decreases, so does the complex impedance. To the best of our knowledge, this is the first time that relationships between the electrical properties of friable sand and grain size dispersion have been studied.

## 1 Introduction

The goal of this study is to look into the connections between the electrical properties of friable sand and grain size dispersion. Previous studies attempted to solve the electrical properties of natural rock samples. Many parameters in natural rock samples' electrical properties are contradictory (according to concentration and texture). As a result, we seek an artificial sample that avoids the majority of these parameters while demonstrating the effect of grain size alone.

Sand is a mixture of granular materials finer than gravel and coarser than silt ( $> 0.009$  mm and  $< 0.0625$  mm). It ranges in size from 0.06 to 2 mm [12, 13, 16, 42]. Sand is founded based on erosion, broken pebbles, and rock weathering. Small cracked pieces of coral, bone, and shell can also be used to create sand on

beaches. Sand can be considered as a textural soil type [3, 5, 7, 9, 31]. Sand is constituted of poorly consolidated coarse aggregate such as rock fragments, mineral particles, or oceanic materials [2–4, 6, 10, 48]. It is mainly made of silicate minerals and silicate rock granular particles. Quartz is the most dominant mineral in the sand as it possesses highly resistant properties to weather [11, 15, 32, 38, 39]. Amphiboles and micas are also found in sand and other common rock-forming minerals [30, 40]. Sand is mostly made up of grey or tan quartz and feldspar [43, 46, 47]. Depending on the particle grain size, the sand is divided into four classes, 1 Very coarse ( $> 5$  mm), 2 Coarse (2.0 mm to 4.75 mm), 3 Medium (0.425 to 2 mm), 4 Fine-grained (0.075 to 0.425 mm) [34–37] (Kharangarh et. al. 2020). Figure 1 shows the grain size dispersion. This paper aims to study the relationships between the electrical properties of friable sand with grain size dispersion.

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**Fig. 1** Different grain sizes of the measured samples

## 2 Sample preparation, characterization techniques and experimental results

Sand accumulations are present in nearly all regions of Egypt [8]. Sand samples were collected from Wadi El-Natrun in the east, where fine sediments of the Miocene and Oligocene are present [1, 10, 14, 45]. For the determination of grain size dispersion, 11 soil specimens were sampled after sieving (Fig. 1). Samples were differentiated by sieving them with 5 mm, 3.15 mm, 2.5 mm, 1.6 mm, 1 mm, 0.75 mm, 0.5 mm, 0.63 mm, 0.4 mm, 0.25 mm, and 0.056 mm sieves. These specimens were compressed in a cup with suitable dimensions, in the form of tablets for electrical properties measurements. The dimensions were one inch ( $\sim 2.67$  Cm) in diameter and  $\sim 15$  Cm in thickness (to avoid the fringing and stray capacitance [28, 44]).

LCR Hitester Impedance Analyzer (Hioki 3522-50) was used to measure the electrical properties. Electrical properties were recorded at room temperature ( $\sim 25^\circ\text{C}$ ) and relative humidity ( $\sim 55\%$ ) using a frequency range of  $10^{-4}$  to 100 kHz and a voltage of 1 V [23, 25, 26, 33]. A homogeneous mixture of specimens was used to ensure that the specimen is representative of the grain size used. Because variations in texture or tortuosity can alter electrical properties, sample homogeneity eliminates this factor [27]. See this page for more information on electrical measurements [18–22, 24].

Electrical measurements were made on samples, of thin shape disks, with a diameter to thickness ratio of 5 to 1. A technique of two electrodes (Agilent dielectric test fixture 16451B) was used. Data were measured using a Hioki 3522-50 LCR Hitester Impedance Analyzer. Samples dimensions were chosen to avoid the fringing effect and other related (stray, capacitive ...) effects. The samples used are dry and measured in an evacuated desiccator [23].

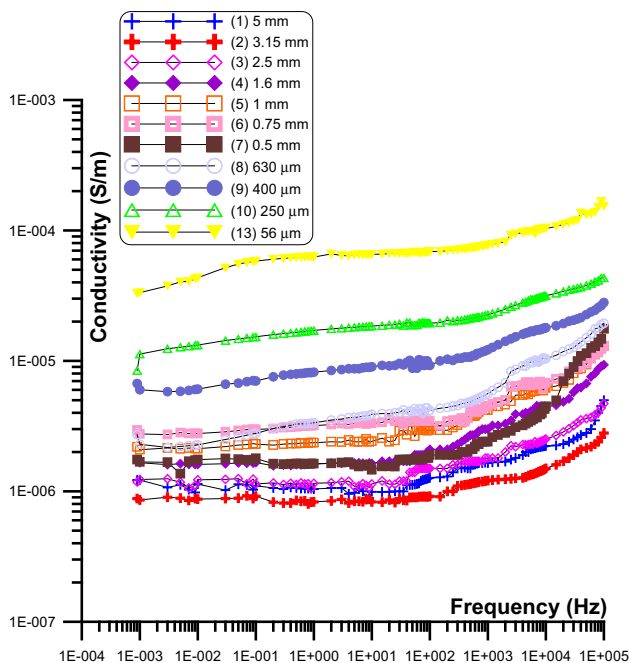
The impedance ( $Z$ ) or the admittance ( $Y$ ) can be used to characterize the electrical properties of the samples. The admittance  $Y = G + j\omega C$ , where  $G$  is the parallel conductance of the sample (Ohm $^{-1}$ ),  $j = \sqrt{-1}$ ,  $\omega = 2\pi f$  ( $f$  is the frequency), and  $C$  is the parallel capacitance of the sample (in Farad). The impedance  $Z$  is given by:  $Z = R_s + \frac{1}{j\omega C_s}$ , where  $R_s$  and  $C_s$  are the series resistance (in Ohm) and capacitance (in Farad), respectively. The complex conductivity  $\sigma^* = \sigma' + j\sigma''$ , where  $\sigma' = \omega\varepsilon''$  and  $\sigma'' = \omega\varepsilon'$ ,  $\varepsilon''$  and  $\varepsilon'$  are the dielectric loss and dielectric constant, respectively.

The series and parallel capacitance and resistance were measured at different frequencies. The complex relative dielectric constant could be written as  $\varepsilon^* = \varepsilon' - i\varepsilon''$ , where the real part of the complex dielectric constant  $\varepsilon' = C_p d / \varepsilon_0 A$  and the imaginary part  $\varepsilon'' = G_p d / \omega \varepsilon_0 A$  is related to the measured parameters,  $A$  being the cross-sectional area of the sample,  $d$  its thickness,  $\varepsilon_0$  the permittivity of free space ( $8.85 \times 10^{-12}$  F/m),  $\omega$  the angular frequency,  $G_p$  the parallel conductance, and  $C_p$  the parallel capacitance [41].

## 3 Electrical characteristics discussions

Change of conductance values is a result of many variables in the specimens. These variables could be mineral concentrations, grain shape, grain size, pressure, temperature, and many other variations [18–22]. Each specimen has a certain concentration of semi-conductor or semi-insulator materials. Electrical properties are affected by the connections between all elements (texture or tortuosity of mixture). Even when the different components of the samples are collected from different materials, then the controlling factor is the net result of the net concentration of semi-conductor or semi-insulator materials. All of these elements' texture and tortuosity, as well as how they are arranged together, are very effective parameters for controlling electrical properties.

Figure 1 shows the grain size dispersion. The conductivity variation with frequency as a function of grain size dispersion is depicted in Fig. 2, (5 mm, 3.15 mm, 2.5 mm, 1.6 mm, 1 mm, 0.75 mm, 0.5 mm, 0.63 mm, 0.4 mm, 0.25 mm, and 0.056 mm). The capability to pass electrical flow is called conductivity. This possibility is proportional to the ion concentration in the sample. These conductive ions are formed by dissolved salts, materials, or compounds in the sample. The higher the conductivity of the sample, the more dissolved ions there are. It is noticed from the curves that the conductivity does not show much change with the change of frequency (especially for low frequencies  $< 100$  Hz). There is a slight variation of conductivity at relatively higher frequencies ( $> 100$  Hz). There are two general slopes for nearly all the curves. The first slope (at relatively low frequencies,  $< 100$  Hz) is defined by a very gentle slope for conductivity with the increase of frequency (slope  $\sim 0$ ). The second slope ( $\sim 0.17$ ) is defined by a more or less increase of conductivity with the



**Fig. 2** Shows the variation of the conductivity with frequency as a function of grain size dispersion (5 mm, 3.15 mm, 2.5 mm, 1.6 mm, 1 mm, 0.75 mm, 0.5 mm, 0.63 mm, 0.4 mm, 0.25 mm, and 0.056 mm)

increase of frequency at relatively high frequencies ( $> 100$  Hz). There is no definite frequency to differentiate between the first and second slopes. Only curve (13) has three slopes with slopes (0.1, 0, and 0.18) from low to high frequency. Also, these three (slopes) regions change by decrease or increase (in frequency range) from one specimen to another.

Generally, as the frequency increases the conductivity increases as a direct result of the energy increase of charged particles. The links of the semi-conductor grains (clusters) increase with the increase of their concentration and with the increase of frequency. All the specimens used here behave as semi-insulators. Generally, an increase in frequency activates charged particles and elements to overcome energy barriers and become more semi-conductive (conductivity values increase).

Figure 3 shows the variation of the dielectric constant with frequency as a function of grain size dispersion (5 mm, 3.15 mm, 2.5 mm, 1.6 mm, 1 mm, 0.75 mm, 0.5 mm, 0.63 mm, 0.4 mm, 0.25 mm, and 0.056 mm). It is noticed from the curves that the dielectric constant shows much change with the change of frequency. There are two general slopes for nearly all the curves. The variation of dielectric constant (first slope) at relatively higher frequencies ( $> 100$  Hz) is more or less, has a gentle slope. The second slope ( $< 100$  Hz) is defined as a very steep slope (slope  $\sim -0.9$ ). There is no definite frequency to differentiate between the first and second slopes.

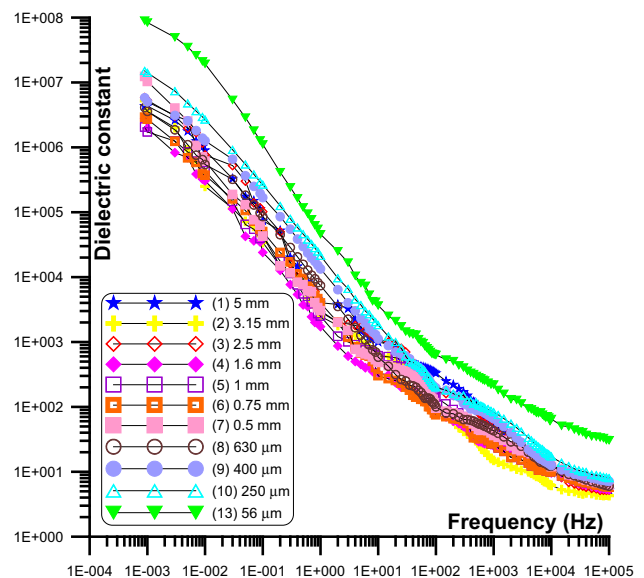
Generally, as the frequency increases the dielectric constant decreases as a direct result of the energy increase of charged particles, and accordingly the

shrinkage of gaps (due to hopping) between grains. When the grain size in the samples is smaller, then the porosity is smaller, and accordingly, the dielectric constant will be higher. The small insulating distances between semi-conducting clusters or grains motivate high values of the dielectric constant.

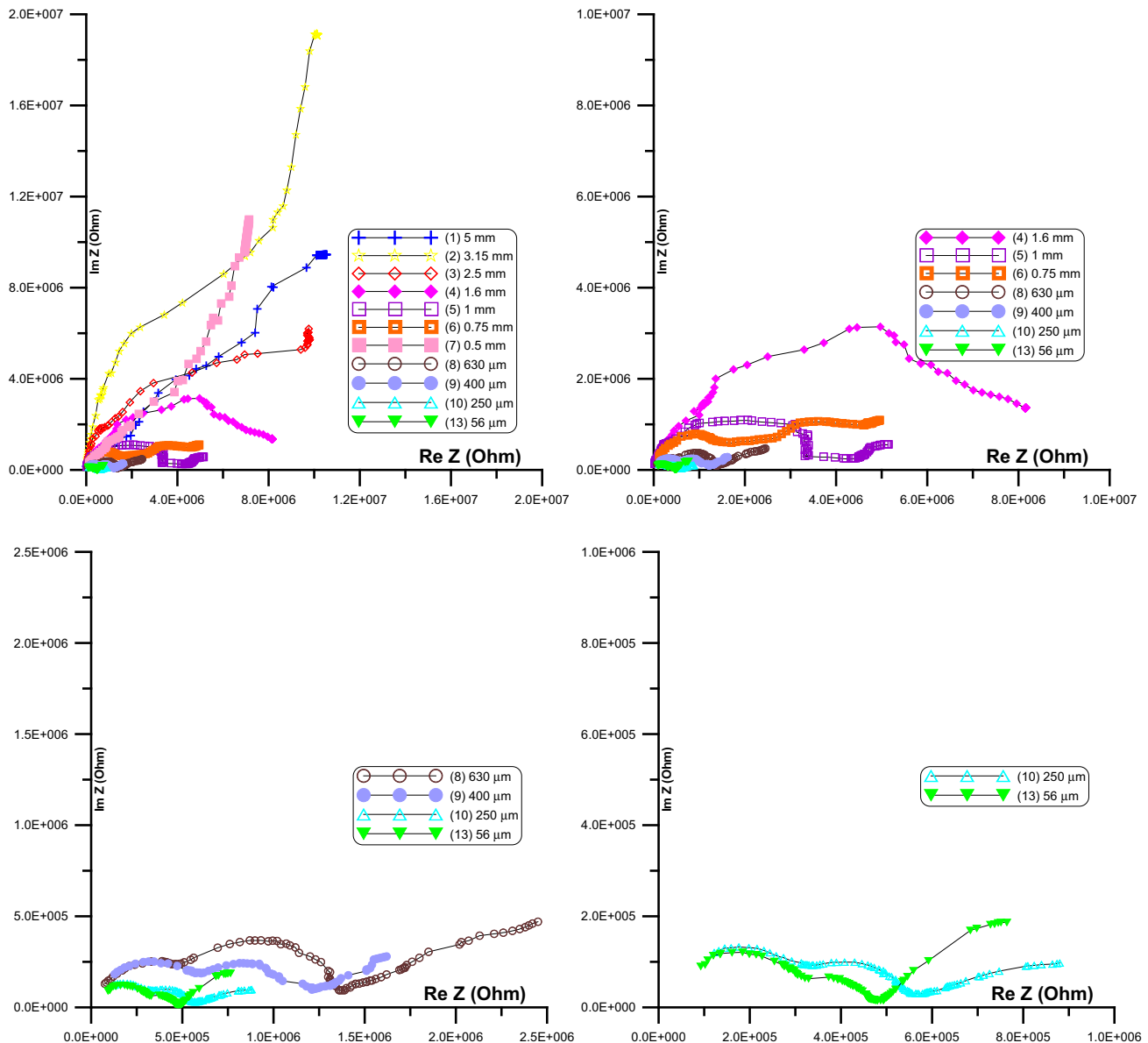
Generally, an increase in frequency activates charged particles and elements to overcome energy barriers and become near to each other (dielectric constant values increase).

The variations of minor and major elements in the specimens cause the dielectric constant values to alter. The specimens are arranged nearly identically based on conductivity and dielectric constant values. Frequency increases and accordingly, charged particles are activated to overcome energy barriers between clusters or grains to become closer to each other's and, finally, dielectric constant values increase [28].

Figure 4 shows the dispersion of complex impedance with grain size dispersion (5 mm, 3.15 mm, 2.5 mm, 1.6 mm, 1 mm, 0.75 mm, 0.5 mm, 0.63 mm, 0.4 mm, 0.25 mm, and 0.056 mm). The group of curves could be divided into three groups; (A) samples that show an arc (for samples 1, 2, 3, and 7), (B) samples that show one semicircle (for samples 4, 5, and 6), and (C) samples that show a semicircle attached to an arc or (maybe) two semicircles attached (for samples 8, 9, 10 and 13). These three groups of curves show different impedances. The first one has the highest real impedance values ( $\sim 10$  M $\Omega$ ) and the highest imaginary impedance values ( $< 20$  M $\Omega$ ). The second one has fewer real impedance values ( $< 8$  M $\Omega$ ) and fewer imaginary impedance values ( $< 3$  M $\Omega$ ). The last one has the highest real impedance values ( $< 2.5$  M $\Omega$ ) and



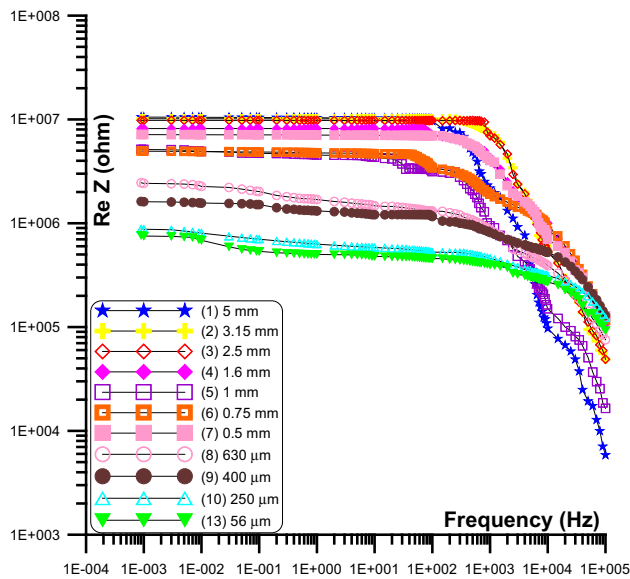
**Fig. 3** Shows the variation of the dielectric constant with frequency as a function of grain size dispersion (5 mm, 3.15 mm, 2.5 mm, 1.6 mm, 1 mm, 0.75 mm, 0.5 mm, 0.63 mm, 0.4 mm, 0.25 mm, and 0.056 mm)



**Fig. 4** Shows the variation of the complex conductivity with grain size dispersion (5 mm, 3.15 mm, 2.5 mm, 1.6 mm, 1 mm, 0.75 mm, 0.5 mm, 0.63 mm, 0.4 mm, 0.25 mm, and 0.056 mm)

the highest imaginary impedance values ( $< 200 \text{ k}\Omega$ ). Curves of the highest real and imaginary impedances belong to the bigger grain sizes and the other curves of the lowest real and imaginary impedances belong to the smallest grain sizes. From the curves (Fig. 4A), sample 7 (0.5 mm) does not obey this rule; this could be due to the presence of some other grain sizes in the sample or due to the presence of some unclean sands (inclusions of clay). As a general rule, as grain size decreases, conductivity and dielectric constant increase while complex impedance (real and imaginary) decreases. The samples can tell the difference between the contributions of grain interiors and grain boundaries to the overall conductivity of the sample.

There is a clear notice from the electrical measurements that changes in grain sorting or mixing, or any other textural parameter, may change the electrical properties of the samples. Samples 9 and 13 (250 μm and 56 μm) show two semicircles in addition to an arc. The arc could be associated with the Warburg impedance and the first semicircle, attached to it, is associated with the interfacial impedance between the grain surfaces. The second semicircle (for high frequencies) is associated with the bulk properties of the samples (grains) themselves. The arcs (or lines) at the impedance plane are an indication of the imaginary impedance concerning the real impedance. If the semi-circle is big then the imaginary and/or the real

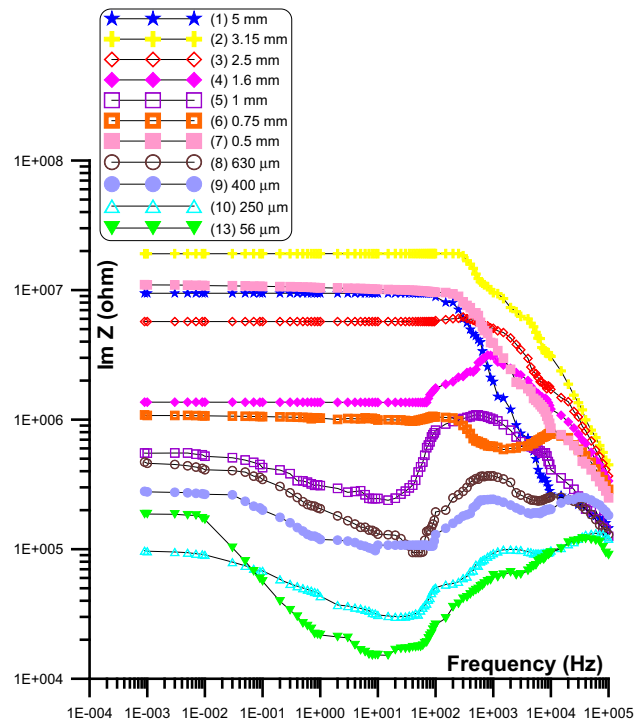


**Fig. 5** Shows the variation of the real impedance with grain size dispersion (5 mm, 3.15 mm, 2.5 mm, 1.6 mm, 1 mm, 0.75 mm, 0.5 mm, 0.63 mm, 0.4 mm, 0.25 mm, and 0.056 mm)

impedance is high, and accordingly, the total semi-conducting paths at the sample are small. With the decrease of semi-circle volume, then the imaginary and/or the real impedances are smaller, and accordingly, the total semi-conducting paths in the sample are increasing. In our case, semi-conducting paths come from the charges at the interfaces between grains. When the semicircle changes from one semicircle to two connected semicircles, then the true bulk properties of the material begin to appear at higher frequencies [17]. Figure 4 shows many details as a trial to show the details of each sample concerning the other one. There are many different radii and different centers of semicircles according to the effect of the bulk material in the specimens, i.e., not only one definite semicircle [29], Gomaa and Abou El-Anwar 2019). The texture of the minor and major compositions changes and the electrical properties change as a result.

Figure 5 shows the variation of the real impedance with grain size dispersion (5 mm, 3.15 mm, 2.5 mm, 1.6 mm, 1 mm, 0.75 mm, 0.5 mm, 0.63 mm, 0.4 mm, 0.25 mm, and 0.056 mm). It is clear from the curves that all samples show no changes with the increase of frequency up to  $\sim 1$  kHz for all grain size dispersion. Above  $\sim 1$  kHz, the real impedance begins to decrease dramatically with the increase of frequency for all grain size dispersion. The dispersion with the smallest grain size has the lowest real impedance, while the dispersion with the largest grain size has the highest real impedance.

Figure 6 depicts how the imaginary impedance varies with grain size dispersion (5 mm, 3.15 mm, 2.5 mm, 1.6 mm, 1 mm, 0.75 mm, 0.5 mm, 0.63 mm, 0.4 mm, 0.25 mm, and 0.056 mm). From the curves, it is clear that many samples (5 mm, 3.15 mm, 2.5 mm, 1.6 mm,



**Fig. 6** Shows the variation of the imaginary impedance with grain size dispersion (5 mm, 3.15 mm, 2.5 mm, 1.6 mm, 1 mm, 0.75 mm, 0.5 mm, 0.63 mm, 0.4 mm, 0.25 mm, and 0.056 mm)

1 mm, 0.75 mm, and 0.5 mm) show no changes with the increase of frequency up to  $\sim 100$  Hz. Above  $\sim 1$  kHz, the imaginary impedance begins to decrease dramatically with the increase of frequency for some samples (5 mm, 3.15 mm, 2.5 mm, 0.5 mm). Another group of samples (0.63 mm, 0.4 mm, 0.25 mm, and 0.056 mm) shows some stability for very low frequency ( $< 0.01$  Hz), then it decreases and increases with the increase of frequency. This could be to the fluctuations of the imaginary impedance from Warburg to interfacial to bulk impedances. The smallest grain size dispersion has the lowest imaginary impedance and the largest grain size has the highest imaginary impedance (at a certain frequency  $\sim 10$  Hz).

Table 1 shows the change of electrical conductivity, dielectric measurement, real and imaginary impedance (Ohm) for various samples at 100 kHz.

## 4 Conclusion

The present work is a trial to explore the effect of the grain size dispersion on the electrical properties of some friable sand samples at a frequency range from  $10^{-4}$  to 100 kHz. Some friable sand samples were sieved. The grain size dispersion used in this article ranges from 5 mm up to 56  $\mu$ m (5 mm, 3.15 mm, 2.5 mm, 1.6 mm, 1 mm, 0.75 mm, 0.5 mm, 0.63 mm, 0.4 mm, 0.25 mm,

**Table 1** Shows the change of electrical conductivity, dielectric measurement, real and imaginary impedance (Ohm) for various samples at 100 kHz

| $\varepsilon'$ | $\sigma$    | ReZ (Ohm) | ImZ (Ohm) | Sample name   |
|----------------|-------------|-----------|-----------|---------------|
| 5.2584         | 5E−6        | 5850      | 145,100   | (1) 5 mm      |
| 4.2801         | 2.8E−6      | 49,400    | 448,320   | (2) 3.15 mm   |
| 5.2095         | 4.704E−6    | 48,900    | 367,560   | (3) 2.5 mm    |
| 5.2584         | 9.3298E−6   | 107,000   | 336,480   | (4) 1.6 mm    |
| 5.7965         | 1.306172E−5 | 16,460    | 125,320   | (5) 1 mm      |
| 5.7965         | 1.3039E−5   | 117,000   | 288,850   | (6) 0.75 mm   |
| 6.1878         | 1.7684E−5   | 128,000   | 248,680   | (7) 0.5 mm    |
| 5.9938         | 1.9434E−5   | 75,400    | 129,390   | (8) 0.63 mm   |
| 7.1049         | 2.8038E−5   | 129,000   | 182,310   | (9) 0.4 mm    |
| 7.961          | 4.329E−5    | 122,000   | 120,320   | (10) 0.25 mm  |
| 30.521         | 0.00015393  | 92,500    | 90,020    | (13) 0.056 mm |

and 0.056 mm). Each grain size was collected, and compacted under a suitable pressure to form a compressed disk with suitable dimensions. The changes in electrical properties, in this case, are the result of grain size dispersion only. Grain size, mainly, with texture or tortuosity is the main control of the electrical properties. It was noticed from the electrical properties of curves that the conductivity and dielectric constant increase with the decrease of grain sizes. The increase in conductivity is the due increase in conducting clusters between grains (charges on the surfaces of the grains). The increase in dielectric constant has resulted from the decrease of porosity between grain sizes (decrease in the volume of air between grains). This is due to the decrease in pore throats between grains as grain size decreases. Furthermore, as grain size decreases, so does the complex impedance. To the best of our knowledge, this is the first time that relationships between the electrical properties of friable sand with grain size dispersion have been studied. Electrical properties were able to track changes in specimens caused by different levels of grain size. Many condensed measurements and discussions are required to study the effect of grain sizes quantitatively.

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## Author contributions

The author writes the manuscript, analyzed and interpreted all the data. All authors read and approved the final manuscript.

**Availability of data and material** All data generated or analyzed during this study are included in this published article [and its supplementary information files].

## Declarations

**Conflict of interest** The authors declare that they have no competing interests.

**Ethics approval and consent to participate** We ensure the quality and integrity of our research.

**Consent for publication** We ensure that the publisher has the author's permission to publish research findings.

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