CHARACTERISTICS OF SODIUM CHLORIDE (NACL) UNDER DC, AC AND IMPULSE CONDITIONS

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ABSTRACT

It is generally known that a few types of salts are used for soil treatment to obtain low resistivity soil; namely Copper and Sodium Sulphate, Sodium Carbonate, Sodium Chloride and Sodium Hydrate. The aim of this study is to investigate the characteristics of Sodium Chloride (NaCl) under direct, variable frequency and impulse conditions. The test data revealed that the resistivity values of the salt obtained under DC and AC at 50Hz are similar, whereas a significant reduction in the resistivity was observed as the frequency was increased. A much lower resistivity value was also observed under high current magnitude. The characteristics of NaCl are investigated under low and high-magnitude impulse currents in order to better understand its effect on sand-salt soil mixtures, where the results have been presented in a previous study [1].

Keywords: Salt, DC, AC, impulse conditions, resistivity, permittivity.

1. INTRODUCTION

A few types of salts namely: Copper and Sodium Sulphate, Sodium Carbonate, Sodium Chloride and Sodium Hydrate have been used for soil treatment to obtain low resistivity soils for earth impedance purposes. The curves of resistivity versus water content percentage for a number of salt solutions have been published by Tagg [2], which showed that for the same amount of salts dissolved in water, Copper Sulphate produces the highest resistivity and Sodium Hydrate yields the lowest resistivity. This clearly shows that different salts affect soil resistivity, and may have different characteristics.

In this work, the characteristic of NaCl was studied. It is one of the most common salts used to reduce soil resistivity for earthing system applications. The characteristic of NaCl used in this work is quantified more accurately under low-magnitude DC and AC, and then with high-magnitudes impulse current conditions. This allows comparison with existing published data and the establishment of the main changes in characteristics introduced at higher current magnitudes.

2. LOW-MAGNITUDE DC AND AC TESTS

2.1 Test Circuit

Figure 1 shows the laboratory test arrangement consisting of a power supply, voltage and current transducers, and a test cell, used for DC and AC tests. For dry NaCl, current measurement was obtained with a current shunt of 70kΩ and a commercial current transformer with a ratio of 0.1V/A was used for wet NaCl during both DC and AC tests.

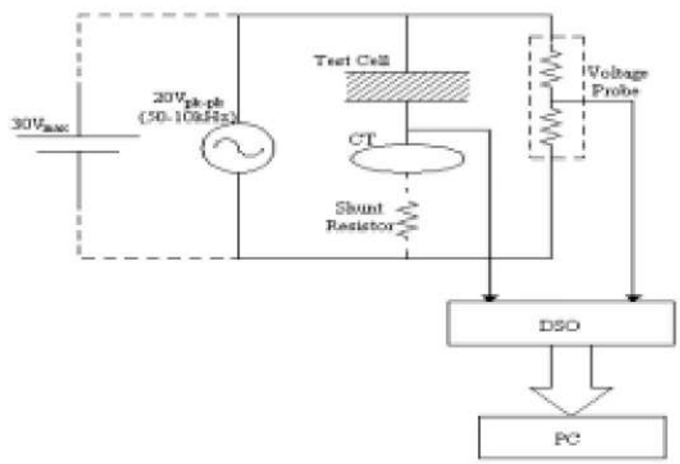
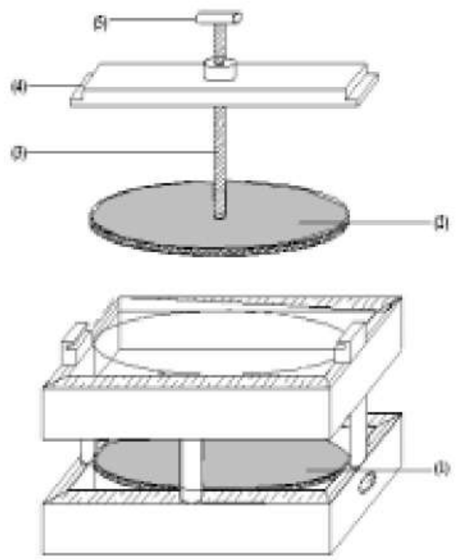


Figure 1: Test circuit for AC and DC characterisations.

2.2 Test Cell

Figure 2 shows the construction of the parallel plate adopted in this test designed essentially for characterisation tests at low voltages and variable frequency tests [3]. This parallel plate, which provides a uniform electric field is designed to BS 1377 recommendations [4] for measuring soil resistivity. It consists of two parallel discs of 24.7cm-Diameter. Disc (1) is fixed to the bottom of the test cell, whereas the top disc (2) is connected to a threaded rod (3). The threaded rod can be adjusted with a support structure (4), which is attached directly to a beam. A handle attached to the top end of the rod (5) allows the adjustment of the spacing between the discs. This handle can be tightened to compress the NaCl in order to minimise sharp edges and air gaps which might exist in NaCl particles, and between the beam electrode and the test medium. Tests were carried out on dry NaCl and NaCl mixed with 5%, 10% and 15% of water contents. This work was conducted independently of a recently published study [3].



(1) Lower electrode; (2) Top electrode; (3) Adjustment rod; (4) Latching beam; (5) Handle
Figure 2: A schematic diagram of the parallel plate test cell.

2.3 DC TESTS

Using the test circuit shown in Figure 1, the characteristics of dry NaCl and NaCl mixed with 5%, 10% and 15% water content under DC conditions were determined. A stabilised DC power supply with a variable voltage level up to 30V was used. However, for tests on wet NaCl, the applied voltage was limited to 8V due to high currents through the test cell (above 1.5A), which exceeded the ratings of the DC stabilised power supply. For each test medium, the tests were repeated at least three times, and the measurements on wet NaCl were taken within a short period of time after it had been prepared in order to minimise the effects of water settling, heating and drying. A satisfactory repeatability was achieved in these tests. Table 1 shows the measured average resistivity values as the applied voltage was varied from 5 to 30V for dry NaCl, and from 2V to 8V for wet NaCl.

Table 1: Measured values of resistivity of NaCl.

Water content (%)	0	5	10	15
NaCl resistivity (Ωm)	4.8M	88	64	26.5

2.4 AC TESTS

2.4.1 Calibration with Air Filled Gap

The purpose of this test was to calibrate the measurement system adopted in this study. An air gap of 1cm was set between the disc parallel-plate electrodes. An AC voltage of up to 10V peak and frequencies up to 1kHz were applied to the test cell.

Current measurement was obtained with a shunt resistor of 70kΩ. Figure 3 shows typical voltage and current waveforms obtained at 1kHz. A current of 2.8μA peak in quadrature with the voltage was measured, which indicated its capacitive nature. The measured capacitance, C_m was derived to be 44.6pF, which was within 5% of the theoretically calculated capacitance, C_t of 41.4pF.

The small difference between measured and calculated capacitance values could be due to inaccuracies in air gap dimensions. Non-uniform electric field distribution, caused by high field intensity around the electrode edges, may also introduce errors in these measurements.

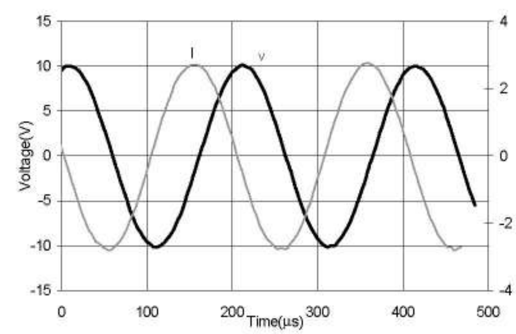


Figure 3: Voltage and current waveshapes for AC tests on air gap at 1kHz.

2.4.2 AC Characterisation of Dry NaCl

Voltages of up to 10V peak magnitudes and of frequencies up to 10kHz were applied to the test cell filled with dry NaCl. It was observed that the current leads the applied voltage by a phase angle, θ, in both low and high frequency regimes, as shown in Figures 4a and 4b respectively. Careful examination of the voltage and current traces of dry NaCl showed that the current exhibited a predominantly capacitive behaviour at low frequencies (f<1kHz), while the conduction current becomes more apparent at high frequencies (f>1kHz). Considering these observations, it is therefore possible to represent dry NaCl by an R-C parallel circuit. Both R-C parameters are non-linear functions of the frequency in which the parallel capacitance, C, becoming less significant as the frequency of the source is increased and R becoming dominant in the high frequency regime.

Based on this observation, each parameter can be estimated from the following equations;

The impedance of the test sample is

$$Z = |Z| \angle \theta \tag{1}$$

which is also written as

$$\frac{1}{Z} = \frac{1}{R} + j\omega C \tag{2}$$

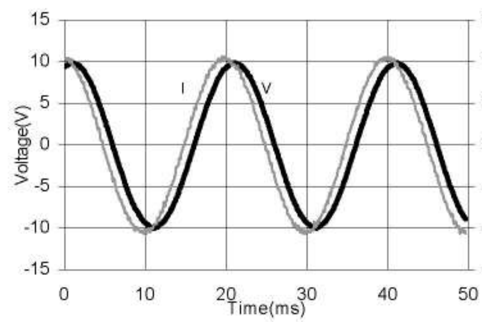
This yields the resistance component

$$\frac{1}{R} = \left|\frac{1}{Z}\right| \cos\theta \tag{3}$$

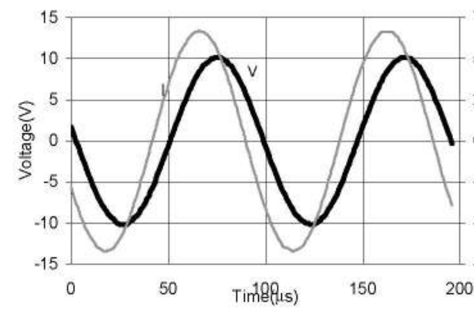
and the capacitance component

$$C\omega = \left|\frac{1}{Z}\right| \sin\theta \tag{4}$$

Figures 5a and 5b respectively show the frequency dependence of R and C of dry NaCl. Based on the known dimensions of the test sample (surface area of the disc electrode, S and distance of air gap, d), the corresponding values of resistivity, ρ and relative permittivity, ε_r were derived. The resistivity value was calculated from $R=\frac{\rho}{S}d$, whereas the relative permittivity ε_r was derived from $C = \varepsilon_r \varepsilon_o \frac{S}{d}$ in which ε_o is the permittivity of free space. These quantities are also shown on Figures 5a and 5b.

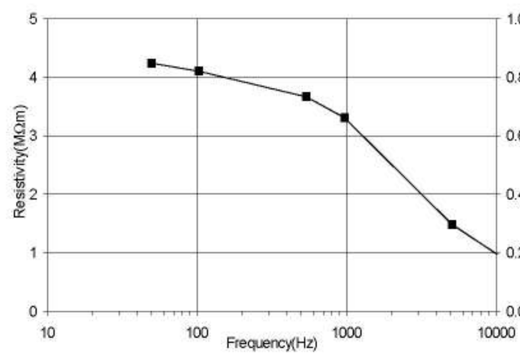


a) Low frequency regime, at 50Hz

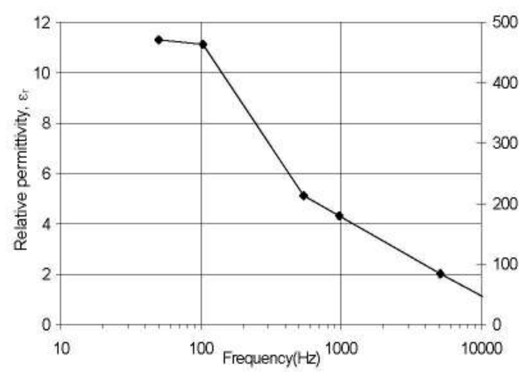


b) High frequency regime, at 10kHz.

Figure 4: Voltage and current waveforms of dry NaCl.



a) Resistivity and resistance



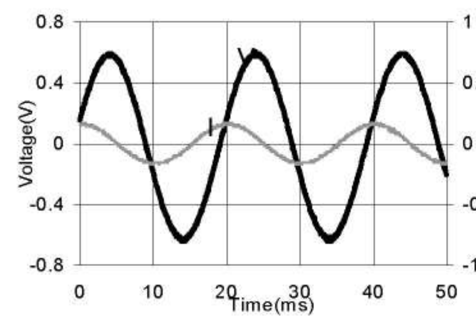
b) Relative permittivity and capacitance

Figure 5: The effect of frequency on dry NaCl.

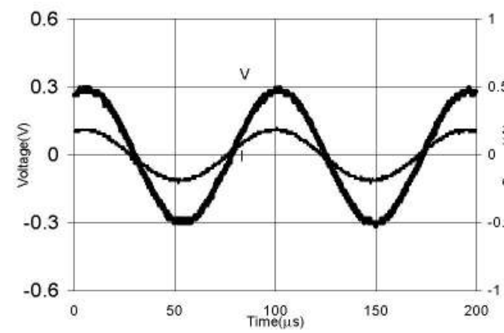
As can be observed in Figure 5a, the resistivity of dry NaCl decreases from 4.2MΩm at 50Hz to 0.8MΩm at 10kHz. The relative permittivity of dry NaCl decreases from the value of 11 at 50Hz down to a value close to 1 at 10kHz (Figure 5b). A decrease in relative permittivity with frequency can be explained using simple dielectric theory, as described by Schon [5].

2.4.3 AC Characterisation of NaCl with Controlled Water Content

As clearly shown by Tagg [2], the resistivity of salt solutions was found to decrease with increasing percentage of NaCl in the solution, due to higher conducting paths in wet NaCl. Using a similar test circuit, as shown in Figure 1, AC tests were conducted on wet NaCl for various frequencies from 50Hz up to 10kHz. Similar voltage and current waveshapes as in dry NaCl were observed in tests with wet NaCl, in which the current leads the voltage by a phase angle, θ in both low and high frequency regimes. Another similar observation is the capacitance predominance at lower frequencies, while the conduction dominates at higher frequencies. Figures 6a and 6b show voltage and current waveforms for NaCl mixed with 10% of water content, respectively at low and high frequency regimes. Similar voltage and current trends were observed for NaCl mixed with 5% and 15% of water content. However, it was noticed that for the same frequency, higher phase angles, θ, were obtained with higher conductivity test media. At a frequency of 50Hz, the current waveform was found in quadrature with the voltage for NaCl mixed with 15% of water, which showed that it is dominantly capacitive, but as the frequency was increased, all NaCl mixtures became more resistive. Therefore, wet NaCl can also be represented as an R-C parallel circuit. A similar procedure, as given in Equations (3) and (4) was used to estimate R and C. Figure 8a shows the effect of frequency on the resistance and the corresponding resistivity of wet NaCl. The trend is similar to that obtained for dry NaCl where the resistance/resistivity were found to decrease with frequency. However, much lower resistivity values of less than 100Ωm were measured. Moreover, the capacitance and its corresponding relative permittivity were also found to decrease with frequency (Figure 7b). However, higher relative permittivity values were observed in wet NaCl, which are in a range of 1000's. This is due to small phase angles measured in this case which reduces accuracy.

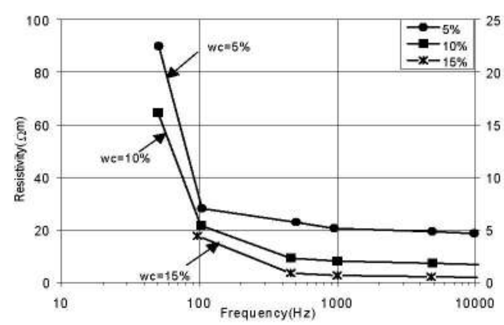


a) Low frequency regime, at 50Hz.

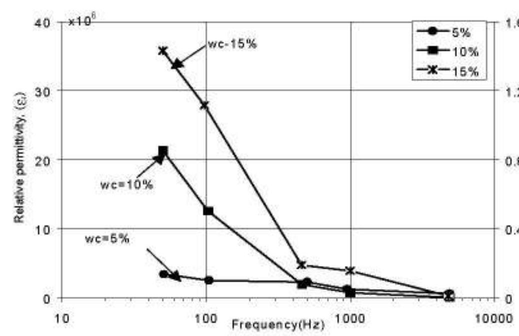


b) High frequency regime, at 10kHz.

Figure 6: Voltage and current waveforms for NaCl mixed with 10% of water content.



a) Resistivity and resistance.



b) Relative permittivity and capacitance.

Figure 7: The effect of frequency on wet NaCl.

3. Impulse Tests

3.1 Test Circuit

A double exponential test circuit was used (Figure 8), where it was possible to generate high voltages up to 50kV, and high current impulses up to 5kA. The impulse source was configured as a current generator by paralleling three low inductance 0.15µF, 65kV capacitors. The capacitor banks were connected to the dc charging unit and switched via an SF_6 spark gap, where a pulse transformer is used for triggering of the spark gap. A tail resistor of 21kΩ and a front resistor of 50Ω were adopted in this test circuit in order to obtain the required front and tail waveshapes and also to limit short circuit current magnitudes at breakdown. The current measurement was achieved with a commercially available current transformer of sensitivity $0.1VA^{-1}$ and a response time of 20ns. The voltage measurement was achieved using the D-dot probe with a ratio of 10300:1 and a response time of 40ns.

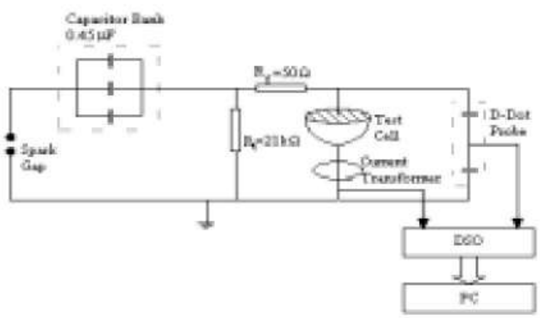


Figure 8: Impulse test circuit

3.2 Impulse Characteristics of NaCl Mixtures

Impulse tests were conducted on NaCl mixed with controlled water contents using a hemispherical test cell (container outer diameter of 25cm, electrode diameter of 1.8cm) was used for NaCl mixed with 5%, 10% and 15% water content. As expected for dry NaCl, very high initial oscillations were observed on the current front (Figure 9). These are thought to be caused by capacitive effects. A slow decay on the voltage and current traces is also observed which could be due to low conduction in dry NaCl.

Figures 10a and 10b show selected typical voltage and current traces for wet NaCl, at the low and high conductivity and no observable obvious effect of ionisation could be seen on the current traces. This may be explained by the low resistivity of the salt preventing build up of high potentials which are known to be responsible for discharges within the bulk material. The conduction process in salt however was found to be non-linear and dependent upon the applied impulse voltage/current. Figure 11 illustrates this non-linear behaviour for NaCl mixed with 5%, 10% and 15% of water. It was observed that the non-linearity is more pronounced at current magnitudes below 1kA where the resistance of the test sample decreased very rapidly. Here, the resistance was determined from the ratio of voltage at the instant of peak current to the magnitude of the peak current which eliminates the inductive effect.

A careful examination of the voltage and current traces revealed that the higher the percentage of water content inside the NaCl (i.e: higher conductivity of test media), the higher the oscillations on the front impulse voltage. However, the origins and causes of these oscillations are still not well understood.

4. NaCl Resistivity Characteristics: Summary

Figure 12 shows the measured resistivity values for wet NaCl with 5, 10 and 15% water content under various conditions of applied voltage. As can be seen, the measured resistivity is highest for direct voltage. Only a small change was seen at 50Hz. However, as the frequency of the applied voltage was increased, a significant reduction in the resistivity was observed. This somewhat peculiar trend was also reported by Schon [5]. Under the extreme stress of high-magnitude impulse currents, the resistivity falls to a substantially lower value compared with the DC case (approximately a fall of 90%). The high current magnitude may be responsible for thermal effects which contribute to the decrease of resistivity. On the other hand, under high frequency dielectric losses can contribute significantly to the conduction and polarisation losses.

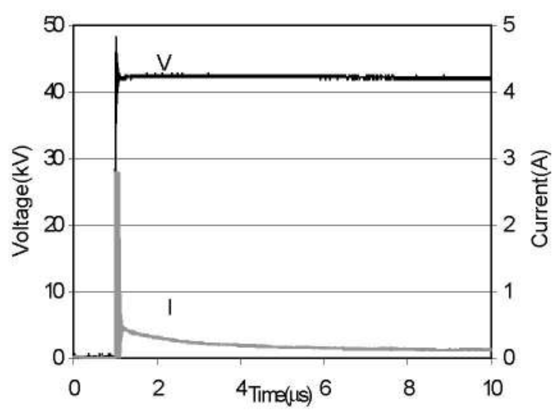
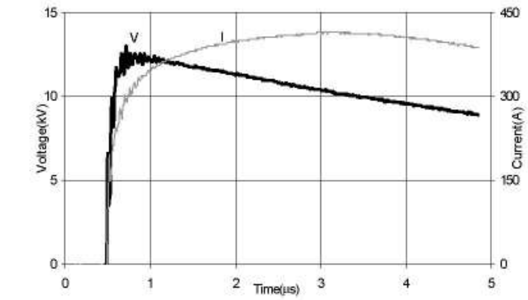
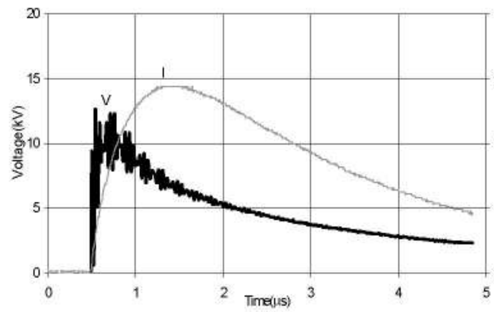


Figure 9: Voltage and current traces of dry NaCl at charging voltage of 43kV.



a) NaCl mixed with 5% of water



b)

NaCl mixed with 10% of water

Figure 10: Voltage and current traces for wet NaCl with an applied voltage of 12kV.

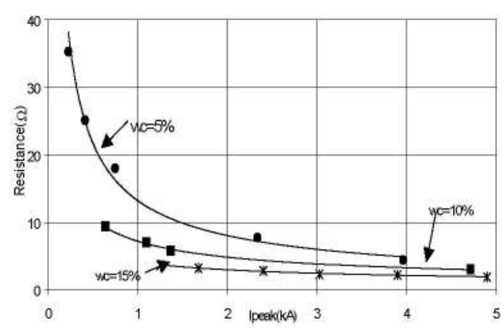


Figure 11: Resistances (Ω) vs current peak (kA) for wet NaCl.

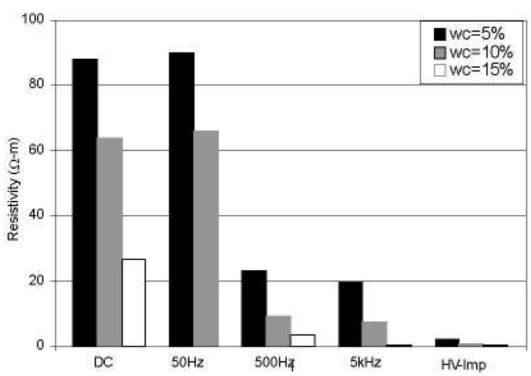


Figure 12: Wet NaCl resistivity values for different applied voltage types.

5. Conclusion

The characteristics of NaCl were investigated under direct, variable frequency and high impulse currents. The test results were used to derive both resistivity and permittivity data. The measured NaCl resistivity magnitudes under DC conditions were found to be similar to AC values at 50Hz. Another important observation relates to relative permittivity; at 50Hz NaCl exhibits a permittivity of 11 when dry with a strong decrease with increasing frequency. In addition, this permittivity was found to increase rapidly with water content but this may be affected by accuracy problems due to small phase angles.

When impulse tests were conducted on NaCl with various water contents to investigate its conductive behaviour, its resistance was found to decrease with increasing currents for any given water content. This behaviour was attributed to thermal and ionisation processes. However, the resistivity of high conductivity test samples (i.e: NaCl mixed with 10% and 15% of water) was found to be less dependent upon current magnitudes.

References

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