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Impulse Characteristics of Various Soil-Enhancement Material Mixtures

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Abstract

Many studies have demonstrated that a reduction in ground impedance value occurs under high-impulse current magnitudes, due to the ionisation process in soil. The degree of the ionisation process was found to be influenced by several factors, such as soil resistivity, the ground electrode's configuration/size, impulse polarity, voltage/current magnitudes and impulse polarity, while in several publications, there was no clear influence of these factors on the ionisation process in soil. Given the uncertainty in the characterisations of grounding systems under high-impulse conditions, it can be difficult to relate the impulse characteristics to the design of grounding systems. This, however, may be possible to achieve if adequate data is obtained, with more tests and analytical studies being performed. Furthermore, as the use of enhancement materials (EMs) has been shown to reduce ground resistance values, the relevant data, which have been found to be limited, are the impulse characteristics of EMs. The effectiveness of these EMs is mostly presented at low-voltage and low-frequency currents, and so far, there is limited available data on their performance with various water contents (WCs) subjected to high-impulse currents. This paper aims to provide the impulse characteristics of soil mixed with various EMs and WCs. Three types of EM were used, and the initial results show that the performance of EMA has an advantage over the others, due to having the lowest Z_{imp}, current rise and discharge times, and breakdown voltage and times in comparison to other EMs tested in this work.

Keywords: ground electrode; enhancement materials; impulse impedance; impulse characteristics; inductive effect

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1. Introduction

Soil properties are the main parameters that are normally considered in the design of grounding systems, where these properties, among others, include moisture content and chemical content, density, porosity, soil grain size, and temperature, which change the soil resistivity and, hence, the ground resistance and ground potential. Grounding design practice and measurement procedures are commonly guided by established standards and guides, particularly for safety, earth resistivity measurement, and grounding impedance assessment [1–3].

As lower soil resistivity generally supports better grounding performance, a wide range of commercial enhancement materials (EMs) have been applied to reduce soil resistivity and improve grounding effectiveness. Field measurements [4–8] are particularly

valuable because they reflect real installation conditions and capture time variation due to environmental changes, including seasonal moisture variation and the long-term stability of the treated soil. For example, seasonal variability of soil moisture can cause significant variations in grounding behaviour and transient response, which motivates field validation alongside laboratory characterisation [4–8].

Several field investigations and applied studies have reported that EMs can reduce grounding resistance, sometimes substantially, but that the performance depends on installation, soil type, and environmental conditions. Soil treatment using low-resistivity materials has been reported to reduce grounding resistance for different electrode configurations, supporting the practical value of engineered backfill and treatment strategies [5]. Similarly, studies on earthing enhancement compounds in challenging ground conditions, such as rocky areas, highlight that the improvement may extend beyond low-frequency performance and also influence impulse behaviour, which is directly relevant to lightning and switching transients [6]. Earlier work on resistance reduction agents, including industrial byproducts, also supports that material addition can improve grounding performance, but the effectiveness is strongly dependent on material composition and moisture conditions [7,9].

Despite substantial work on grounding improvement at low voltage and low frequency, transient and impulse performance requires separate consideration. Grounding under lightning and fast transients is governed by frequency-dependent soil parameters, electromagnetic effects, and in many cases, nonlinear soil ionisation around electrodes. Modern grounding transient modelling and interpretation, therefore, rely on frequency-dependent soil characterisation and validated transient grounding metrics, including impulse impedance and related measures [3,10–18]. Experimental and modelling studies have shown that soil electrical parameters exhibit frequency dependence, and that this dependence can materially change predicted transient response. This motivates laboratory measurements and modelling frameworks that represent soil permittivity and conductivity as functions of frequency [10–13].

High voltage and impulse investigations further show that backfill and soil type can change breakdown behaviour and discharge processes under severe electrical stress. For commonly used backfill materials such as bentonite, cement, and sand, impulse and alternating high voltage tests have reported distinct breakdown characteristics and the formation of fused structures under certain stress conditions, indicating that material behaviour under high voltage may differ from what is expected from low frequency resistance alone [15]. In addition, soil ionisation effects under lightning impulses can alter effective grounding impedance, and reviews of soil ionisation modelling indicate that reliable interpretation requires careful attention to modelling assumptions and test conditions [16–18]. High-frequency transient response of grounding electrodes is also sensitive to soil dielectric properties, reinforcing the importance of characterising soil and soil EM mixtures beyond only steady-state resistance [19–21].

Although the above literature establishes that EMs can reduce grounding resistance and that transient grounding performance depends on frequency-dependent and nonlinear effects, there remains limited laboratory data that directly quantifies the impulse performance of soils mixed with commercial enhancement materials across controlled moisture conditions. Earlier impulse studies on enhancement materials mixed with sand indicate that impulse behaviour can differ from low-frequency expectations, but broader comparative datasets across multiple commercial EMs and moisture conditions are still needed. To address this gap, this paper investigates the impulse performance of three commercially available EMs used locally, mixed with soil and tested under high impulse conditions, and compares the results against untreated soil. Several moisture contents are considered to quantify how water content interacts with EM mixtures under impulse stress.

In summary, characterisation of the grounding system under impulse can contribute to an optimum design of grounding systems. This is because, under high impulse currents, non-linear behaviour of the grounding system would occur, caused by an ionisation process in soil. This non-linear soil behaviour can improve the performance of grounding systems, where better conduction in soil is expected, which can be considered in the design of grounding systems. As discussed before, studies on a range of soil test media with the effect of impulse polarity, current magnitudes, and test cells have been published to determine the degree of non-linearity in soil, typically defined as critical electric field (E_c). As the soil mixed with EM can be a complex mixture and heterogeneous, in which the impulse characteristics can be different than the soil, more data are, therefore, needed by carrying out more tests and analytical studies.

To address this gap, this paper investigates the performance of three EMs typically used locally, added into the soil, subjected to high impulse conditions, which are then compared with the soil without the EM. Various percentages of water content were also used in these soil–EM mixtures under high impulse conditions. The study is hoped to provide useful data for the power engineers and EM manufacturers to quantify the quality of EM in terms of its performance under high impulse conditions.

2. Test Set-Up

2.1. Test Circuit

In this work, an impulse current generation is adopted, where the current generator consists of: (a) a charging transformer of 3 kVA, 50 Hz, 220 V/50 kV, 15 A/60 mA, (b) 4 units of low inductance capacitor bank of 25 kV, 2 µF and (c) a compressed air spark gap having an energy rating of 25 kJ. Figure 1 shows the experimental arrangement adopted in this study. For high current measurements, a current transformer that can measure 10 kA with fast rise times of 20 ns was used. The resistive divider with a ratio of 1000:1 and a response time of 40 ns was adopted for voltage measurements. Two Digital Storage Oscilloscopes (DSOs) were used for capturing voltage and current signals.

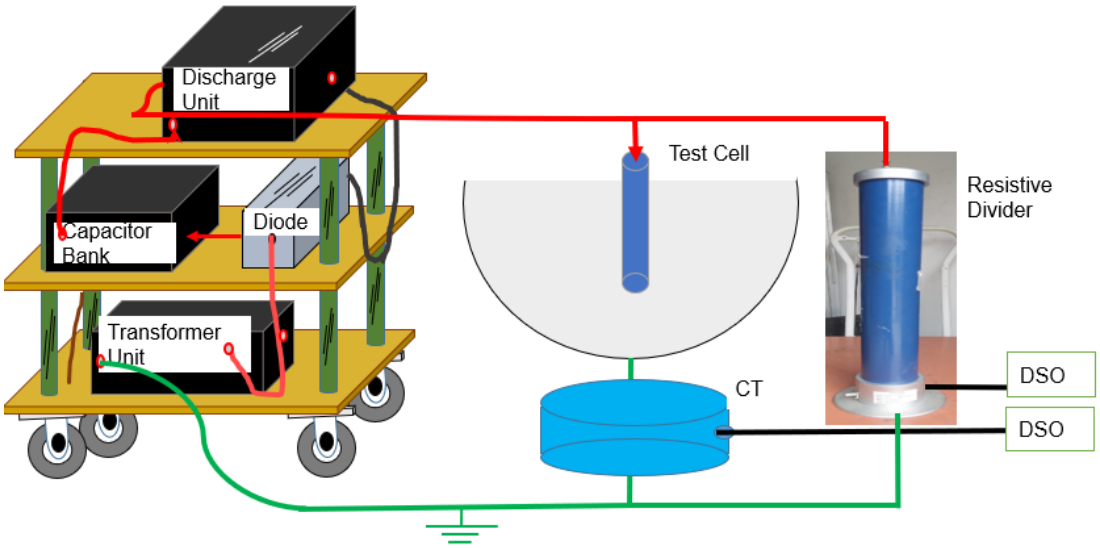


Figure 1. Experimental arrangement used in the study.

2.2. Test Cell and Soil-Mixtures

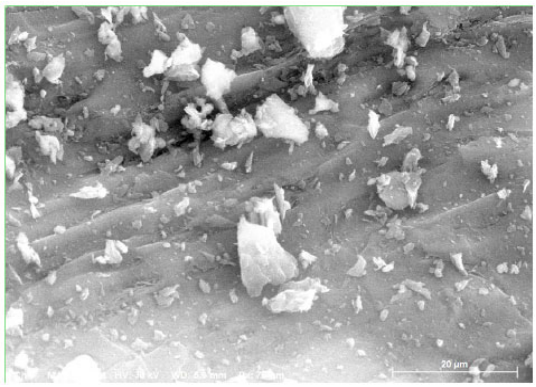
A hemispherical test cell of 60 cm diameter was adopted, where a rod of 16 mm diameter was used as an active electrode. The rod was placed in the middle of the container, to a depth of 15 cm of the soil-mixtures. The supporting structure to support the container

filled with sand mixtures is made of epoxy to avoid any flashover between the metallic container and the surrounding materials. Sand with a grain size of between 2 mm and 10 mm (of which the grain size measurement was achieved from the Civil Laboratory) was used in this work. The soil mixtures consist of sand mixed with three types of EMs with a controlled amount of water content. The percentage of water content and EM was measured, respectively, as the ratio of the mass of water content to dry sand mass and the ratio of the mass of EM to dry sand mass. This is one way to control the consistency of the mixtures, as the medium has a different density. The mixtures were also mixed thoroughly in a separate container before being transferred to the test rig to ensure a uniform distribution of the test media, hence reducing experimental errors.

EMs were also analysed in their element distribution using Scanning Electron Microscopy with Energy-Dispersive X-Ray Spectroscopy (SEM-EDX scanning). Table 1 shows the element distribution of powdered EMs used, where the largest element percentage is carbon. Figure 2a–c shows the images for the EM elements and their sizes. EMA has a very high carbon fraction with minimal silicate/oxide content indicates a comparatively continuous carbon percolation in the sand matrix. Such a network may easily initiate discharge paths at low voltage/current. EMB still forms a carbon-rich phase, but slightly lower than EMA. Notably, higher oxygen/silicate/aluminate content (Si, Al, Ca oxides) introduces insulating patches and interfacial barriers that may interrupt the carbon network. Local pockets of oxide-rich grains and microstructural heterogeneity may contribute to position-dependent field or non-uniformity in its characteristics. EMC has a similar bulk percentage of carbon to EMB, but more elements are found in it, which may isolate carbon clusters and reduce percolation, causing large insulating gaps. These images will be further discussed in the next section.

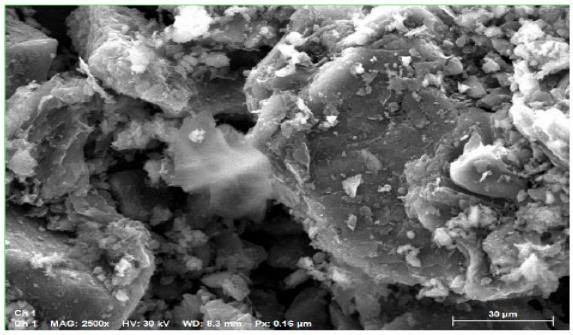
Table 1. Element mass distribution for different types of EM used in the study.

Types of EM	Element Mass Norm (%)							
	Carbon	**Oxygen**	**Sulfur**	**Calcium**	**Aluminium**	**Silicon**	**Gold**	**Iron**
EMA	92.69	3.89	2.89	0.54	No traces	No traces	No traces	No traces
EMB	85.27	10.94	0.23	1.62	0.8	1.14	No traces	No traces
EMC	85.92	8.08	0.5	3.62	0.15	0.65	0.95	0.14

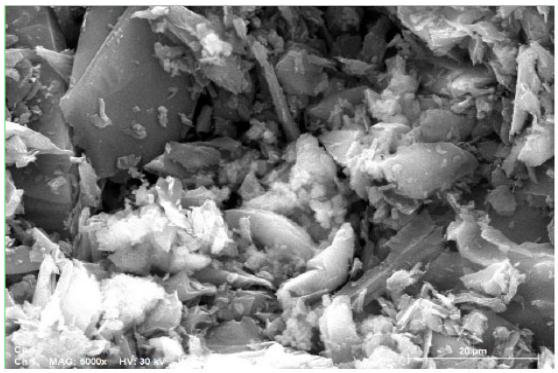


(**a**)

Figure 2. *Cont.*



(**b**)



(**c**)

Figure 2. SEM-EDX scanning images for (**a**) EMA, (**b**) EMB, and (**c**) EMC used in the study.

3. Experimental Test Results

3.1. Voltage and Current Traces

Using the test circuit shown in Figure 1, the characteristics of sand mixtures under high impulse currents were studied. Figure 3a,b show the voltage and current traces of sand + EMC5% + WC5%, respectively, at charging voltages of 5 kV and 20 kV. Though there were some dissimilarities in the degree of initial oscillations on the voltage and current traces, different current rise and discharge times and different magnitudes for different sand mixtures, in general, the traces are similar in its form in which; all traces have fast rise times and current traces follow voltage traces at lower voltage range indicating a predominantly linear resistive behaviour, while current trace discharged faster than the voltage at higher voltage range due to non-linear characteristics of test samples. Discharge times here refer to the time taken for the current traces to reach zero.

It can be seen from the figures that there are initial oscillations on voltage and particularly on current traces at low voltage levels (Figure 3a) and lesser oscillations at higher voltage levels, as shown in Figure 3b. It was described in [20] and demonstrated in [21] that these initial oscillations on the current traces are due to the capacitive effect of the test samples. Due to the capacitive effect, with the combination of the inductive effect of the test circuit and test cell, initial oscillations on the voltage trace were observed. This is also highlighted in [22] that the combination of inductance and capacitance produced high initial oscillations on the voltage trace. As the voltage level was increased, initial oscillations on both voltage and current traces were found to suppress (see Figure 3b), which was due to higher conduction of the non-linear characteristics of test samples as they become pre-dominantly resistive. It was also noticed that when the current trace discharged at faster times than the voltage trace, indicating a non-linearity of the sand–EM mixtures, the initial oscillations on both voltage and current traces were found to lessen.

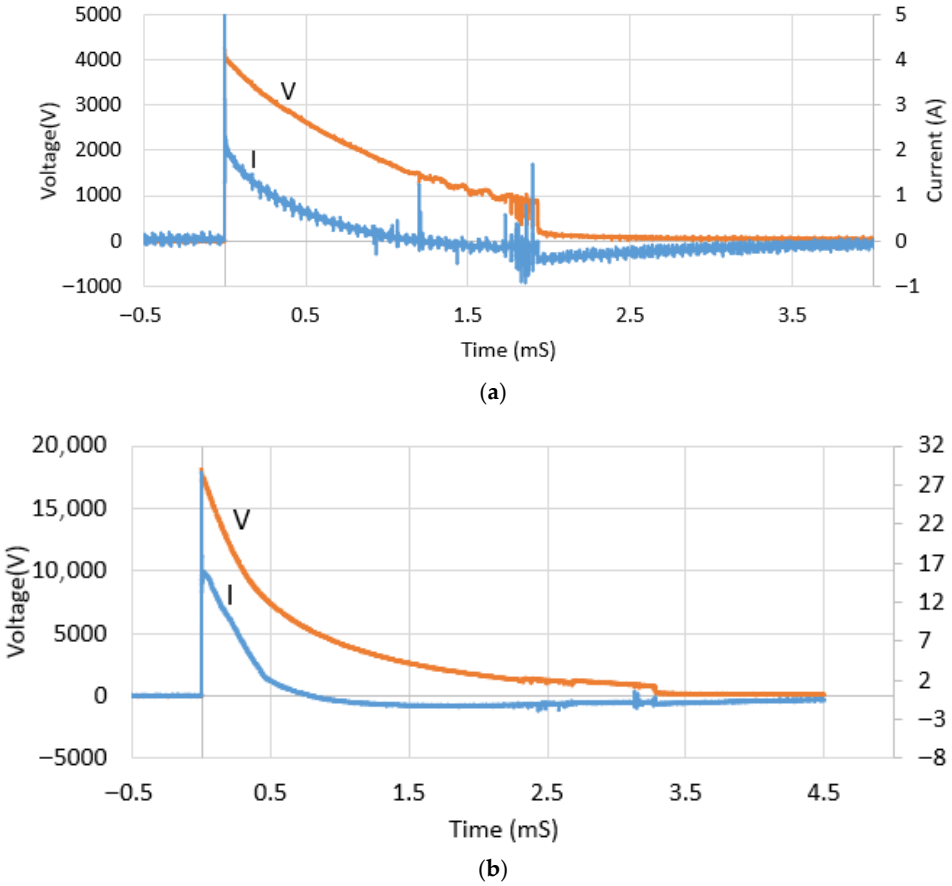


Figure 3. Voltage and current traces of sand mixed with 5%EMC and 5%WC at charging voltage of (**a**) 5 kV and (**b**) 20 kV.

Other than the inductive effect being noted from the initial oscillations on the voltage trace, a high inductive effect was also observed when the current discharged to negative, instead of to zero. This was similar to the demonstration in [21] when the Personal Computer Simulation Program with Integrated Circuit Emphasis (PSPICE) was used, where the current discharged to negative caused by the inductive effect, and this effect is most significant at low voltage levels, like the finding in this work.

The charging voltage was increased until the occurrence of breakdown was observed, as shown in Figure 4, where a sudden voltage collapse was followed by an increase in current. It was observed that the applied voltage at which the breakdown occurred was different for different sand–EM mixtures, as discussed in Section 3.4.

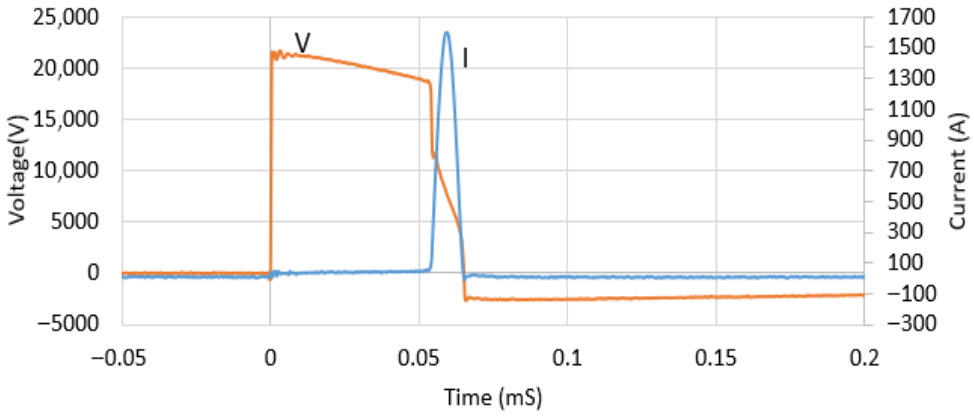


Figure 4. Breakdown voltage of various sand–EM mixtures.

3.2. Current Response Times

In this work, current rise and discharge times are evaluated, where current rise time would provide information on the non-linearity and inductive effect, while discharge times provide information on how conductive the test medium is. It would be expected that the presence of an inductive effect in the test circuit can cause slower current rise times in the non-linear test load than in a linear test load. Similarly, the current trace exhibits faster discharge times for non-linear test loads in comparison to linear test loads. This shows that the information about current rise and discharge times is important to determine whether the sand mixtures have a non-linear characteristic. Simulation work based on PSPICE is conducted in order to demonstrate the relation of current rise and discharge times with the non-linearity of the test medium.

3.2.1. Simulation Study

The test circuit in Figure 5 is used to generate a lightning impulse, a non-linear parameter from the PSPCE, defined as the G-value, which is used to represent non-linear grounding systems. Labelled as G1 in the figure is a non-linear voltage-controlled current source, where the non-linear expressions would need to be placed. In this work, this expression, i.e., Pwr((2.44 $\times$ 10^{-3} * V),1), obtained from curve fitting I = kV^{α}, where I is the current, k is the constant, 2.44 $\times$ 10^{-3}, V is the applied voltage, and the non-linear component, α equals to 1 and 2 to represent for linear and non-linear test loads, respectively. The capacitance (C1) and resistance (R_cir) elements are selected to obtain a typical lightning impulse of 1.2/50 µs, while switch t_open is used to simulate the spark gap of the impulse generator. The inductance (L1) is used to represent the inductance of the test circuit, so that a significant difference between the linear and non-linear test loads is observed, where this value is changed manually. Figure 6a–c show the simulated voltage and current traces obtained for linear and non-linear test loads.

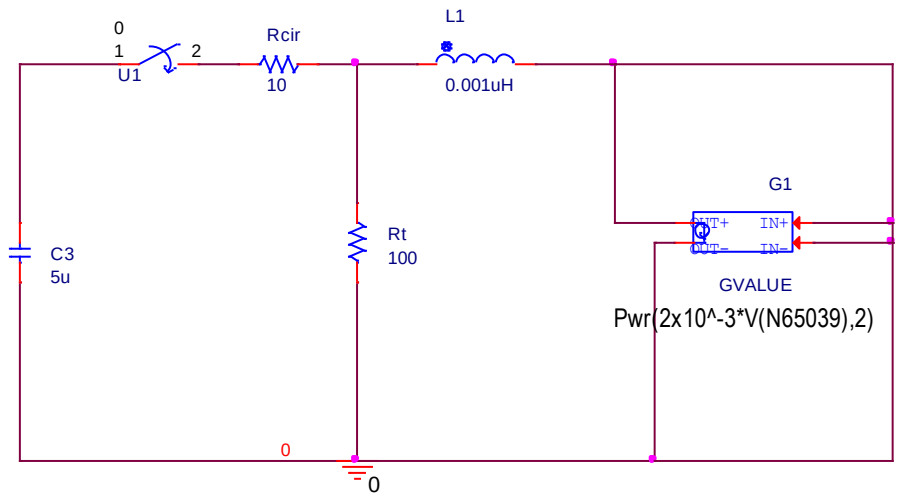


Figure 5. Simulated test circuit.

When L1 was varied, it was noticed that the non-linear test load (Figure 6b,c) was more sensitive to the changes in inductive effect compared to linear test load (Figure 6a); i.e., the larger the inductive effect, the slower the current rise times for the non-linear test load in comparison to the linear test load, which had little change in the current rise times. In a higher degree of non-linearity, α = 3, a breakdown in test load was seen, as shown in Figure 6c, where a sudden drop in voltage was followed by an increase in current. All these observations provide important information in analysing the results, particularly in identifying the non-linear test medium, such that

(a) If there is a dependency on current rise times, the test medium has a non-linear characteristic.
(b) The higher the non-linearity, the more easily the breakdown may occur at lower voltage.
(c) Non-linear test medium would exhibit faster current discharge times than the linear test medium.

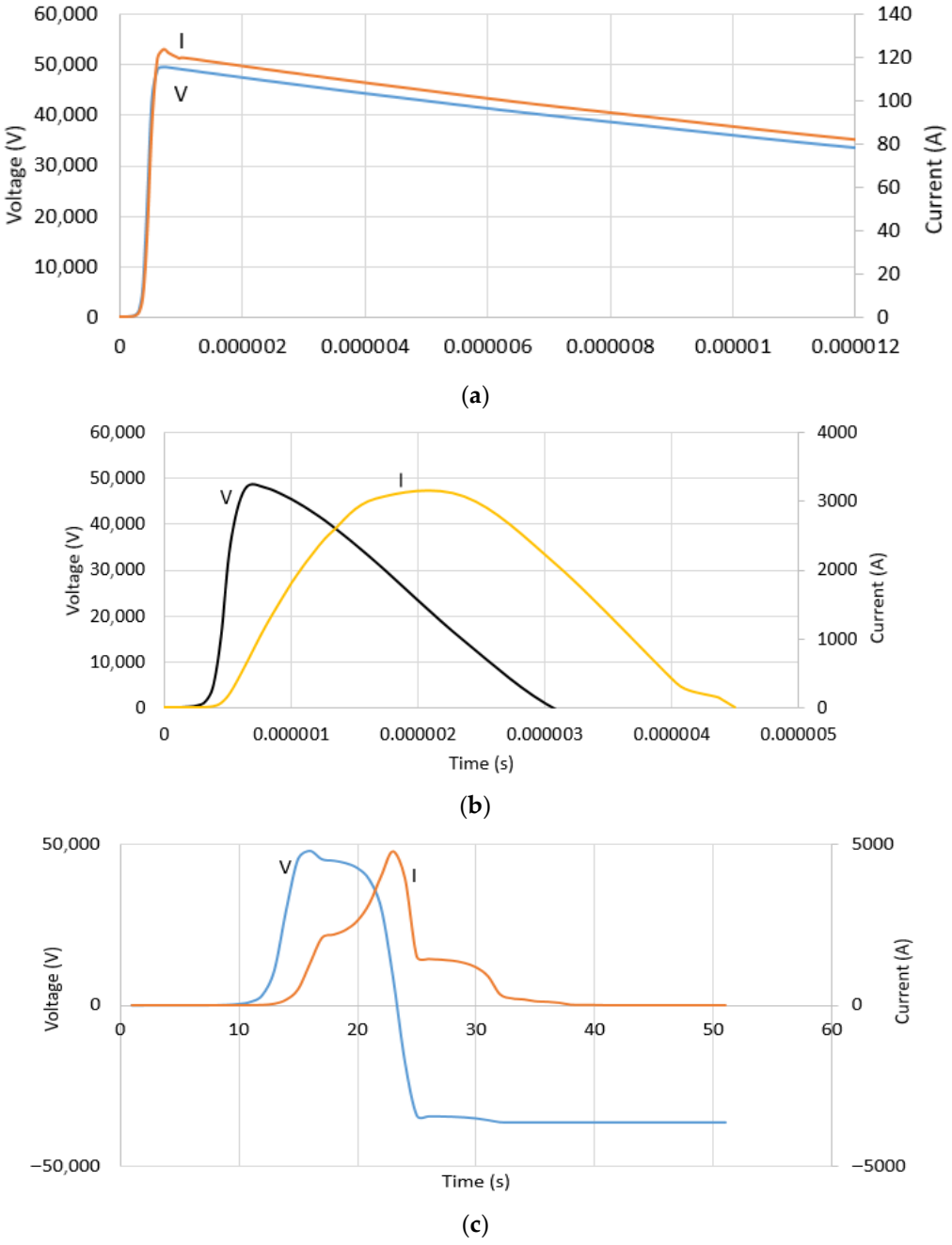


Figure 6. Simulated voltage and current traces (**a**) linear test load, $\alpha = 1$, (**b**) non-linear test load, $\alpha = 2$ and (**c**) $\alpha = 3$.

Appendix A provides the netlist of the simulation file for Figure 5.

3.2.2. Experimental Results on Current Response Times

Figure 7 shows the current rise times for sand mixed with a controlled amount of various EM and WC. For the same 5%WC and EM of 5% and 10%, EMB has the slowest current rise times, while times to peak current for EMC and EMA are close. As has been discussed in Section 3.2.1, the slower the current rise times, the higher the non-linear

behaviour is. This indicates the EMB has the highest non-linear behaviour in comparison to other EMs, which can be due to two main elements present (carbon and oxygen) in EMB, while other EMs have carbon as the main element, and other elements are less than 10%. The mixtures with 10%WC were also found to have the fastest times to peak current, in comparison to other test media. In relation to the simulated results presented in the earlier section that the linear test load has fast rise time and is independent of voltage magnitudes, this shows that all sand–EM with high WC tends to be more conductive and has a linear property.

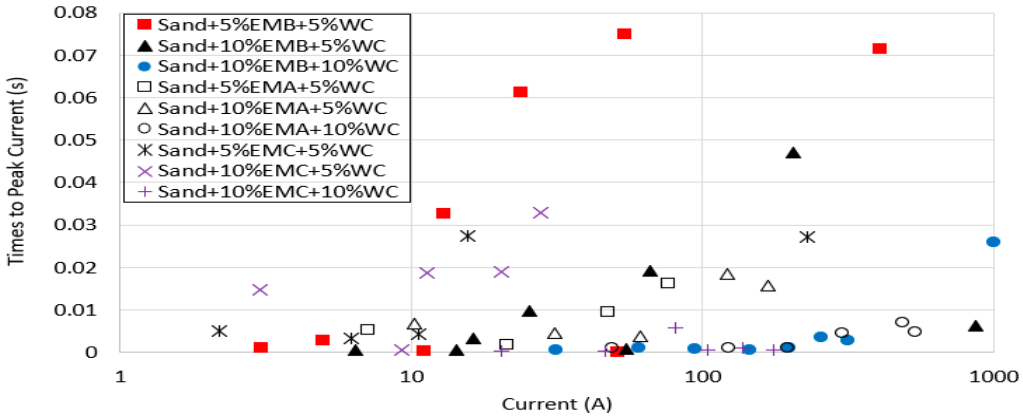


Figure 7. Times to peak current for various sand–EM mixtures.

It was observed that the higher the current, the slower the times to peak current were, except for the sand–EM mixtures of high WC (10%), which were independent of the current magnitudes. This indicates that at high current magnitudes, more nonlinear processes such as ionic, thermal effects, as well as soil ionisation processes may have taken place, which would cause further delay in the current rise times. Inductive effect in the test circuit, in combination with these non-linear conduction processes causing a slower current rise time in the non-linear test cell at higher current magnitudes. Similar observations were seen in [20] when impulse tests were conducted on water filled in hemispherical container, in which, as the current magnitudes were increased, the current rise times of most ground electrodes became slower. This shows that the test medium with ionic conduction, which can be from the chemical content, enhances the non-linearity in the test medium, and in combination with the inductive component of the electrode, increases the current rise times. The results obtained in this work are, however, contradictory to some studies [23] for the impulse tests on the ground electrodes by field measurements, in which the slower current rise at low current magnitudes is observed, while demonstrating faster current rise times at higher current magnitudes due to improved conduction at higher voltage/current.

Figure 8 shows the current discharge times for all test media. It can be seen from the figure that the discharge times decrease with increasing current magnitudes, which can be due to relatively improved conduction of the test media at higher current magnitudes. Similar observations to the current rise times were observed, where for the same 5%WC and EM of 5% and 10%, EMB has the slowest current discharge times. It was discussed earlier that the slow current rise times were caused by high non-linear characteristics in the test medium, which would become slower with the presence of an inductive component in the test circuit and cell. Slow current rise times in EMB, therefore, resulted in slow current discharge times. In high WC, the current discharge times were found to be close, indicating more current paths leading to high conduction in the mixtures.

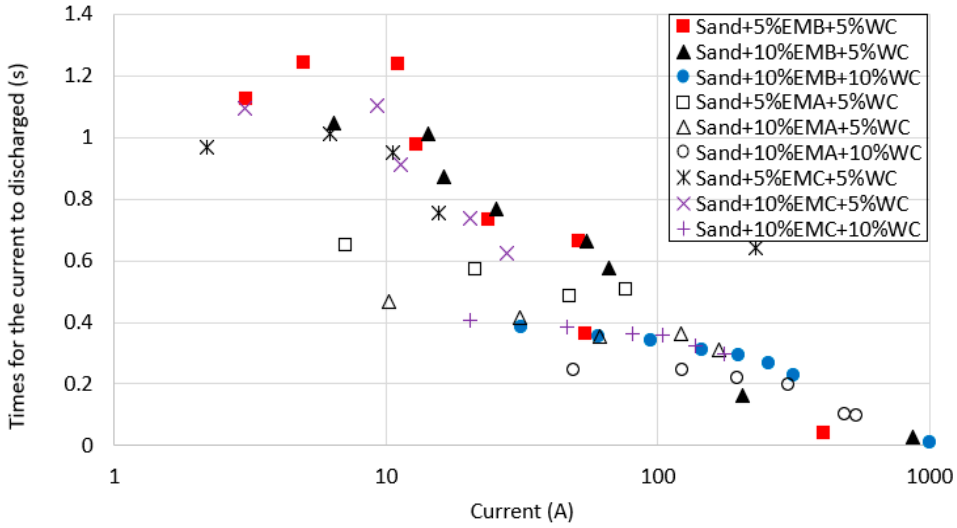


Figure 8. Current discharge times for various sand–EM mixtures.

3.3. Impulse Impedance, Z_{imp}

Impulse impedance, Z_{imp} are expressed as the ratio of the voltage at peak current to the peak current. This measurement is used because at peak current, di/dt is zero, hence minimising the inductive effect. Figure 9 shows the impulse impedance, Z_{imp}, versus current magnitudes for sand mixed with various EM and WC. Z_{imp} decreases with increasing current magnitudes for all test media. The largest reduction in Z_{imp} was seen in sand + 5%EMB + 5%WC. The drop in Z_{imp} when 5% EM was added to sand + 5%EMB + 5%WC, making it to sand + 10%EMB + 5%WC, was found to be the highest drop in Z_{imp} of EMB, more than 70%, indicating that Z_{imp} can be improved significantly in low WC by adding more EMB. On the other hand, with the addition of 5%WC to 10%EM+5%WC, the drop in Z_{imp} was found to be most effective in EMA, which was seen to be more than 70%. All of this indicates that in dry soil, having a low percentage of WC, EMB can be used to lower down the Z_{imp}, while for sand–EMA and sand–EMC mixtures, adding more EM did not reduce the Z_{imp} significantly. This could be due to a high presence of carbon in EMA, more than 90%. For EMB and EMC, the reduction in Z_{imp} became significant in the presence of high WC.

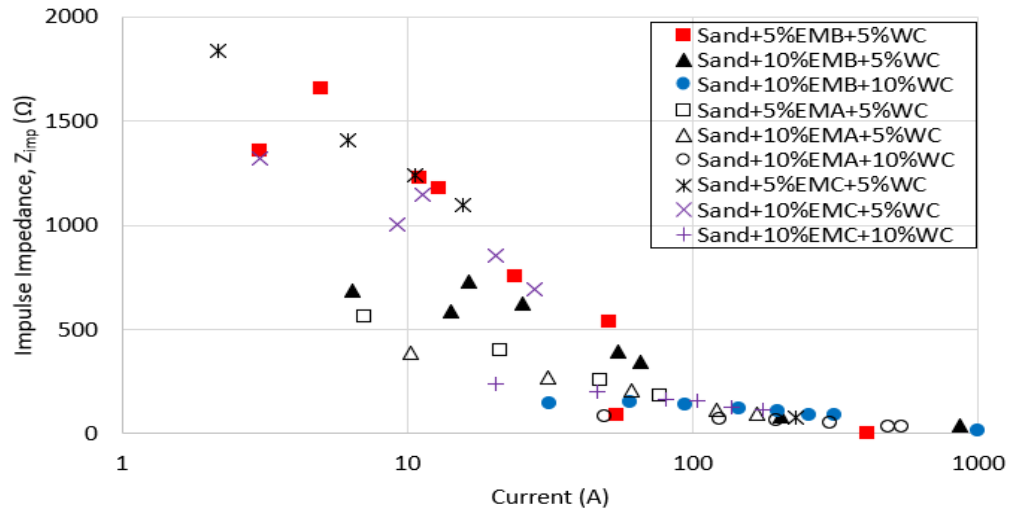


Figure 9. Impulse impedance with increasing current magnitudes for various sand–EM mixtures.

It was noticed that all these three parameters are interrelated to each other; when the current magnitudes were increased, impulse impedance, Z_{imp} values were found to decrease due to the non-linearity of the test media. The evidence of this non-linearity is also observed from an increase in current rise time with increasing currents. As discussed in Section 3.2.2, the increase in current rise times with increasing currents occurred due to non-linear behaviour from the ionic, thermal and ionisation processes, which become significant with the presence of inductive effect in the test circuit. Faster current discharge times with increasing currents were also attributed to improved conduction in test media, in which, at higher current magnitudes, lower Z_{imp} was seen, giving faster current discharge times at higher current magnitudes.

3.4. Breakdown Voltage, V_B

At higher voltage magnitudes, breakdown in the test cell occurred, as observed in Figure 4. Up and down tests can be carried out to obtain the breakdown voltage of each test medium. However, due to high currents which exceeded the ratings of the impulse generator (above 1.5 kA), every time the breakdown occurred, the breakdown voltage, VB, was determined when the breakdown started to occur in the test medium. This approach, in which the determination of V_B is from the observation of the first occurrence of breakdown, is considerably acceptable, as a similar method was used in other published work [20] to obtain the critical electric field, E_c. The voltage level gradually increased until the breakdown in the test medium was observed, as indicated in Figure 3. Figure 10 shows the breakdown voltage for various test media. It was noticed that with the higher percentage of EM and WC, the higher the V_B values are for all test media, except for sand mixed with 10%MEG + 10%WC. Higher V_B in low Z_{imp} can be expected as the low Z_{imp} prevents the buildup of high potential in the test medium, which was also observed in several other publications [4,21]. It was also observed that for the same percentage of EM and WC, EMB had the highest VB, higher by more than 20% to the V_B of EMC, the second highest V_B. It is generally understood that the breakdown voltage corresponds to the dielectric strength of the soil, whereby the lower breakdown voltage corresponds to better soil-sand mixtures, as the full conduction in soil occurs at a lower voltage. From the results, it can be understood that EMA has outperformed other EM, not only having the lowest V_B, but also low Z_{imp}, current rise and discharge times, followed by EMC and EMB. This implies an earlier percolation and stronger field-assisted conduction in EMA, where the performance is consistent with lower Z_{imp} reported earlier and is likely due to a lower percolation threshold and more continuous conductive pathways (particle morphology and carbon content enabling better bridging across moist contacts) in EMA. This could be caused by a high presence of carbon, more than 90% in EMA.

The time to break down, t_B, indicated in Figure 11, gives information on the time taken for the soil to penetrate fully in the test cell. It can be expected that, in some test media, the electrons released from the ground electrode may be diffused by the neutral particles of water, hence requiring a higher voltage and longer time to lead to a complete breakdown. Figure 11 shows the t_B for various sand–EM mixtures, where it can be seen that the soil breakdown is not only dependent on the voltage magnitudes, but also on soil properties. It was noticed from the figure that the t_B decreases with increasing conduction in test media, except for EMC. For the same percentage of EM and WC, EMA is found to have the fastest t_B, in comparison to other test media, indicating that EMA is the most effective test medium in comparison to other EMs.

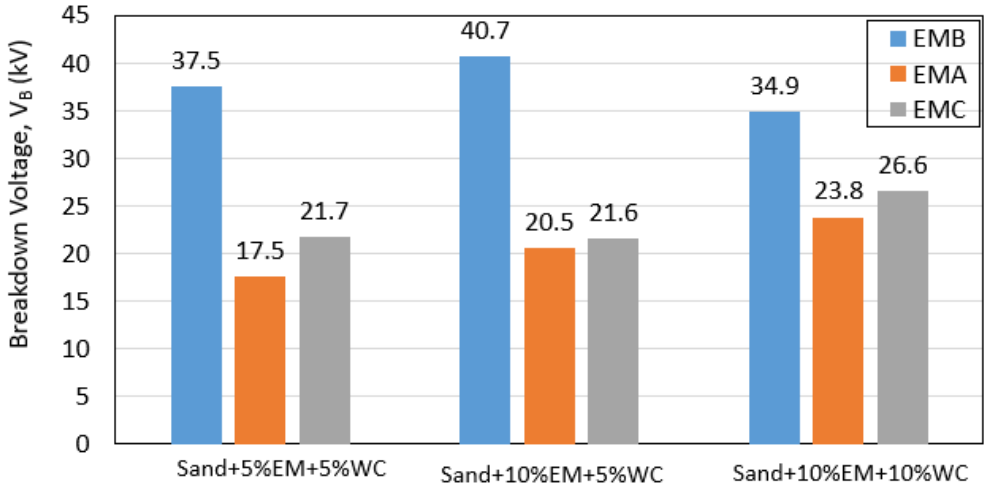


Figure 10. V_B for various sand–EM mixtures.

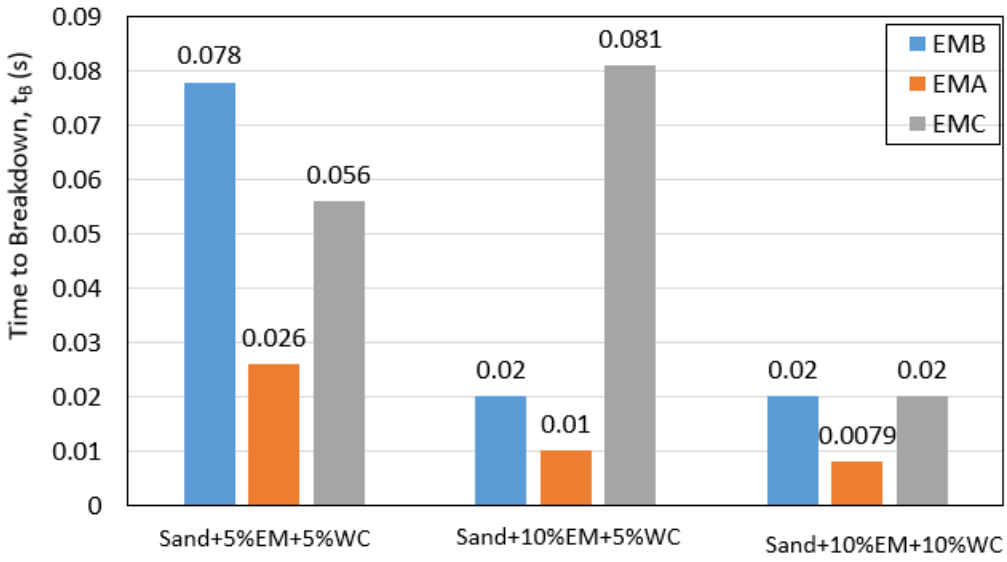


Figure 11. T_B for various sand–EM mixtures.

4. Conclusions

In this work, experimental test results of sand mixed with a controlled amount of EM and water content are presented. Three types of EM were used: EMA, EMB and EMC, mixed with sand and water and filled into a hemispherical container with the active rod electrode placed in the middle and subjected to high impulse voltage.

From these voltage and current traces, Z_{imp}, current rise and discharge times are measured. Oscillations in the voltage and current traces, and different breakdown voltages and times are also discussed. To obtain a better understanding of the behaviour of grounding systems and the parameters influencing the Z_{imp}, current rise times, oscillations, a simulation study utilizing the PSPICE Orcad Lite 17.4 software and comparison with other studies are carried out. The test medium is considered effective when it has non-linear behaviour, which offers better conduction in soil. From the PSPICE simulation, a high degree of non-linearity is observed when the current rise times change significantly with current magnitudes, the breakdown occurs at low voltage and has fast current discharge times.

From experimental work, the current rise times are found to increase with increasing current for all test media, due to the higher non-linear behaviour of the test media at higher current magnitudes, and with the presence of inductance of the test circuit, causing the delay in current rise times to be more significant for the non-linear test load. It is observed

that EMB has the slowest current rise times, hence having the highest non-linear behaviour in comparison to other EMs. Due to slow current rise times in EMB, slow current discharge times were seen in EMB mixtures. For the same percentage of WC and EM, EMA mixtures have the lowest current rise and discharge times, except in test media with high WC, whereby current rise and discharge times are close for all test media.

It is also observed that the Z_{imp} decreased with increasing current magnitudes for all test media, indicating an improved conduction of sand–EM mixtures at higher current magnitudes. The largest reduction in Z_{imp} is seen when 5%EMB was added into sand + 5%EMB + 5%WC, more than 70% difference with sand + 10%EM + 5%WC. On the other hand, with the addition of 5%WC to 10%EM + 5%WC, the drop in Z_{imp} is found to be most effective in EMA, which was seen to be more than 70%. All of this indicates that in dry soil, having a low percentage of WC, EMB can be used to lower down the Z_{imp}, while EMB and EMC, the reduction in Z_{imp} becomes significant in the sand mixtures with a high percentage of high WC.

The voltage at which the breakdown, V_B, occurred and the corresponding time to breakdown, t_B, of the test media are measured. Overall test revealed that EMA, though not having a high degree of non-linearity, is considerably the most effective because not only the lowest V_B and t_B, but also the lowest Z_{imp} and time to discharge to the ground.

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Appendix A

L_L1	N65055 0	0.01 uH
R_Rcir	N65049 N65055	10 TC = 0.0
X_U1	N65039 N65049 Sw_tClose PARAMS: tClose = 0 ttran = 1 u Rclosed = 0.01 + Ropen = 1 Meg	
C_C3	N65039 0	5 u IC = 50 k TC = 0.0
R_Rt	0 N65055	100 TC = 0.0
G_G1	0 0 VALUE { Pwr(2×10^{-3} * V(N65039), 2)}.	

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