FACTORS AFFECTING SOIL CHARACTERISTICS UNDER FAST TRANSIENTS

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***Abstract* - It is well accepted that soil conduction under high magnitude impulse currents is affected by the magnitude of applied current, the type of soil, its moisture content. Also, a threshold electric field intensity (E_c) has been identified above which soil ionisation occurs. However, the published results [1-5] reveal wide range of values of E_c and the effects of many other factors such as impulse polarity, grain size and electrode geometry require further investigation. In this paper, we report test results on various soil media using impulses of negative polarity. The aim of this investigation was to extend an earlier study [6]; by quantifying the effects of impulse polarity, grain size and threshold electric field (E_c) on soil electrical properties.**

Keywords - Soil ionisation, threshold electric field, impulse polarity, grain size, and soil electrical properties.

1. INTRODUCTION

Since the first reported study of non-linear soil behaviour under high currents [1], much research work [2-5] has been directed towards soil characterisation under high magnitude impulse currents. However, very little is published and many aspects need clarification on the factors affecting soil characteristics under high impulse currents.

Here, the effects of impulse polarity, grain size and threshold electric field (E_c) on soil properties are investigated. Laboratory impulse tests on electrode systems inside a sand medium have shown that similar voltage and current impulse shapes are exhibited for both low and high-magnitude impulse conditions for both positive and negative impulses. This was observed for a range of water contents (up to 15%) of the sand. It was found that both the pre-ionisation resistance (R_1) and the post-ionisation resistance (R_2), were higher under negative impulse conditions.

The threshold electric field for initiation of soil ionisation, E_c, was found to be higher under negative impulse, for all water content conditions. In these tests, two test cells were used; a parallel plate test cell providing a uniform field, and a hemispherical test cell providing a non-uniform field profile. It was found that the breakdown electric field magnitudes obtained in the parallel plate arrangement was 7.9kV/cm, higher than E_c of hemispherical test cell, of 5.5kV/cm. This was thought to be associated with non-uniform field distribution in the hemispherical test cell, which encourages ionisation to develop quickly.

For a given applied voltage and water content, the sand with medium grain size was found to have lower R_1 and R_2 compared with sand with fine grain size. However, both grain sizes showed a similar threshold E_c of 5.5kV/cm.

2. TEST CIRCUIT AND PROCEDURE

The same test cell parameters and test circuit, as described in an earlier paper [6] were adopted. Figure 1 shows the laboratory experimental arrangement. Fast response transducers were used for voltage and current measurements [7]. The voltage and current signals were captured on a LeCroy9354C, 500MHz Digital Storage Oscilloscope (DSO), which was linked to a personal computer via a GPIB bus. A 'Labview' application was developed for data acquisition and analysis.

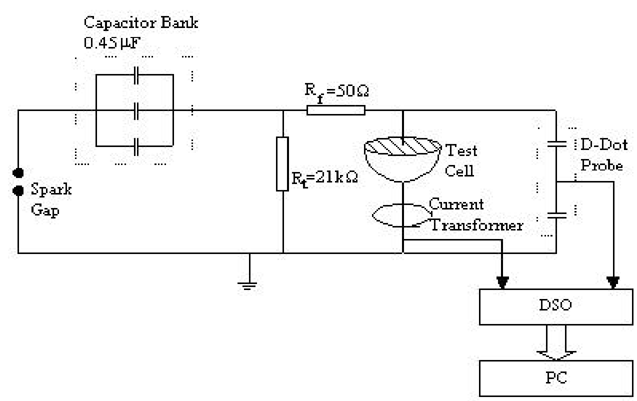


Figure 1: Impulse test circuit.

3. FACTORS AFFECTING SOIL CHARACTERISTICS

3.1 Effect of Impulse Polarity

The characteristics of medium-grain size sand with various levels of water content were investigated and analysed using impulse currents of positive polarity[6]. Here, negative impulse tests were conducted on medium grain sand with various water contents for different charging voltages. Using these test results, the effect of impulse polarity on soil characteristics is investigated.

3.1.1 Current Impulse Shapes under Negative Polarity

Figures 2a to 2c show the voltage and current records for linear and non-linear sand conduction regimes under negative impulse conditions. The voltage and current impulse shapes for linear and non-linear of negative impulse were found to be similar to the positive polarity traces as shown in [6]. At low magnitudes, the current shape appears to coincide with that of voltage (Figure 2b), indicating a linear resistive behaviour. However, for the same sand moisture condition and applied voltage, lower current magnitudes were recorded for similar peak voltages with negative impulses compared with positive impulses. This was rather expected since it is well known that discharges in air occur at lower levels for positive impulses than for negative impulse especially since soil ionisation is thought to occur in the air voids within the soil. Hence, for the same voltage level, less activity was expected for negative impulses.

The non-linear soil behaviour starts to occur when the second current peak is observed. A careful analysis of the voltage and current records reveals that non-linear soil behaviour starts to occur at an applied voltage level above 18kV for each test sample which corresponds to a value E_c of 6.6kV/cm at the live electrode. This value was found to be slightly higher than E_c of positive impulse tests, of 5.5kV/cm [6].

3.1.2 Dynamics of the Ionisation Process under Negative Impulse

Snowden and Erler [8] and van Lint and Erler [9] suggested that the time delay observed in the ionisation current may have information related to streamers formation and the conduction process in soils. From voltage and current shapes of wet sands under high currents, the time-to-initiation of the second current peak, t_1, and the time to second current peak, t_2 were estimated for both impulse polarities. Figure 2c shows the definitions of t_1 and t_2. From Figure 4a and 4b, it can be said that t_1 and t_2 trends for negative impulses were similar to those of the positive impulses. However, for each test sample, the times t_1 and t_2 were found to be higher under negative impulses compared with those under positive impulses. Figure 3 illustrates the differences between t_1 and t_2 for sand with 1% water content under both polarities, and as can be seen, up to 50% difference can occur for both t_1 and t_2.

3.1.3 Effect of Polarity on Soil Ionisation Equivalent Circuit Parameters

As defined in the previous paper [6], the pre-ionisation resistance, R_1 , and post-ionisation resistance, R_2 were measured as the ratio of voltage at I_{peak} to the corresponding I_{peak}, so that any inductive effect in measurement could be eliminated. Figure 4 shows the resistances R_1 and R_2 for sand with different water contents under both impulse polarities.

As can be seen, both R_1 and R_2 curves have a similar trend to those obtained under positive impulse, in which the resistances were found to be decreasing with increasing current magnitudes. This was explained by a thermal process in wet soil, which is responsible for the increase in soil conductivity, thus relatively reducing R_1.

However, as the current magnitude increases the ionisation process will take place in the soil, and this is known to reduce R_2. It was found that for sand with the same water content, the resistances R_1 and R_2 under negative impulse were higher than those obtained under positive polarity. The resistances R_1 and R_2 for sand with 3% of water content are shown for both polarities, and a significant difference (about 100%) can be seen.

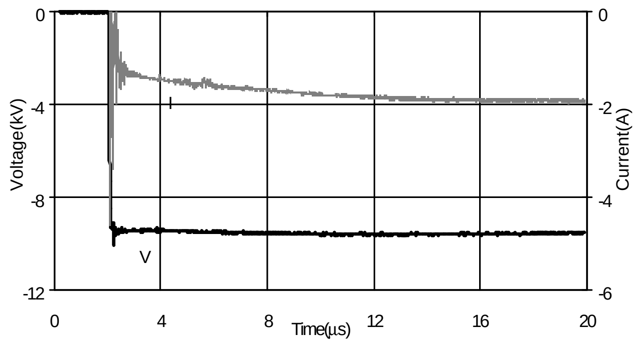
3.1.4 Soil Breakdown Characteristics

Similar breakdown voltage and current traces to those obtained under the positive impulses were observed. The breakdown voltage U_{50} values of negative impulse were measured using IEC 60 [10] method. It was found that U_{50} of negative impulse is independent of the water content inside the sand, which is similar to those of positive impulse. An average magnitude of 26.7kV, which corresponds to E_{50} of 9.8kV/cm, was obtained for wet sand when subjected to negative impulses. This value is slightly higher than that of positive impulse, which was 25.5kV with a corresponding E_{50} of 9.4kV/cm. Again, this is expected because of the polarity effect on air breakdown. These results agree with those published by Petropoulous [5] in which the breakdown voltage of soil under negative impulse was always higher than that under positive impulse.

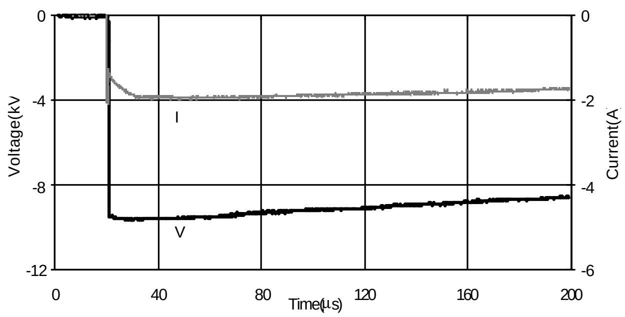
3.2 Effect of Grain Size

The results and discussion presented in earlier work [8] relate to one type of sand test medium. Here, the effect of grain size on electrical behaviour of sand is investigated. It is known that differences in soil grain sizes affect the manner moisture is held within the soil and also will modify the size of air pockets trapped inside the soil, which would in turn affect the soil resistivity. The soil resistivity data for soil with different grain sizes has also been published by both British and American Standards [11-13]. This data shows that for the same soil type, fine grain soil is likely to have higher resistivity than medium or coarse grain soils. However, it is important to note that this published data was obtained with DC and power frequency voltages. Therefore, its validity under impulse conditions may be rather limited.

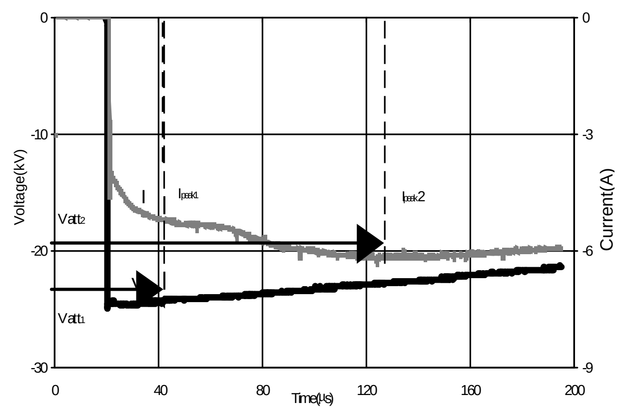
This work compares soil electrical behaviour under high impulse currents of two grades of sand, fine and medium grain sizes. The grain sizes of the sand were first determined according to BS 1377 recommended procedures [14]. With this method, the grain sizes of the medium and fine grain sand samples used in this experiment were determined and are summarised in Table 1.



a) Linear conduction regime



b) Linear conduction regime



c) Non-linear conduction regime

Figure 2: Voltage and current traces under negative impulse conditions (sand with 3% water content).

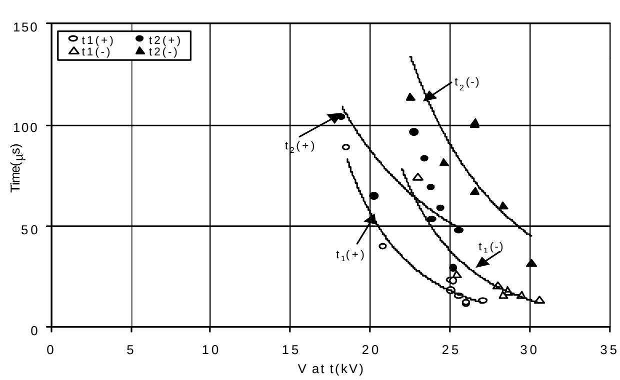


Figure 3: t_1 and t_2 for sand with 1% of water content for both impulse polarities.

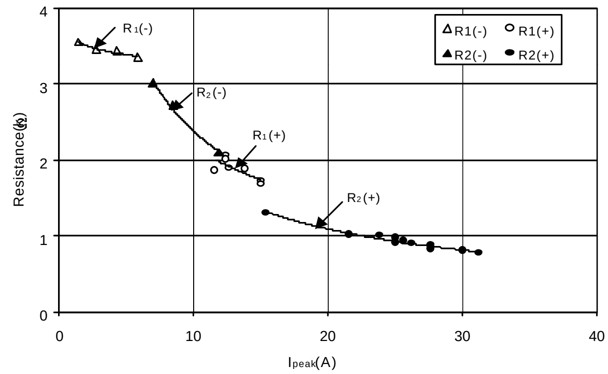


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Figure 4: The effect of impulse polarities on R_1 and R_2 for sand with 3% water content.

Table 1: Types of tested sand

Type of sand	Grain size diameter (mm)
Medium	0.06-0.6
Fine	0.04-0.2

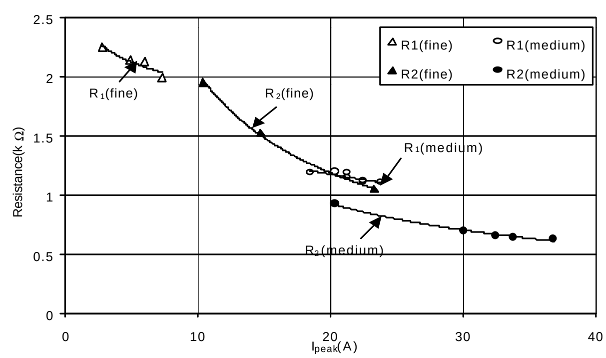

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Figure 5: Pre-ionisation resistance R_1 and post-ionisation resistance R_2 vs peak current for medium and fine grain sand with 5% of water content.

The characterisation test results for medium grain size sand are given in earlier work [6]. Using the same test circuit arrangement and test procedure earlier, tests were conducted on fine grain sand. In the linear conduction regime, the voltage and current magnitudes and shapes for fine grain sand were found to be similar to those of medium grain sand, shown in [6]. The ionisation threshold voltage of 15kV that corresponds to E_c of 5.5kV/cm was also measured for fine grain sand of different water contents and was found to be independent of grain size. These results are similar to those obtained by Cabrera et al. [4] who also found that E_c is independent of grain size for low resistivity soil (less than 10kΩm).

Figure 5 shows R_1 and R_2 of medium and fine grain sands mixed with 5% of water content for different current magnitudes. Again, for fine sand, similar trends were also observed for the pre and post-ionisation resistances, R_1 and R_2. However, it was found that R_1 and R_2 of fine grain are significantly higher than medium grain sand for all water contents. This is attributed to the relatively higher resistivity of fine-grain soils compared with medium-grain soils as published in the standards [11-13].

The average breakdown voltage for this test set up with wet fine-grain sand is 26kV, which corresponds to E_{50} of 9.5kV/cm. This is less than 2% difference of the E_{50}

measured with wet medium-grain sand, presented in the earlier work [6], again, indicating that E_{50} is independent of soil grain size.

3.3 Accurate Measurement of Ionisation Threshold Field, E_c

It is known that the hemispherical container adopted in this study provides non-uniform electric field distribution such that

$$E(r) = \frac{V}{r^2\left(\frac{1}{r_1} - \frac{1}{r_2}\right)}.$$

Figure 6a illustrates the non-uniform electric field distribution within the test cell and Figure 6b shows the schematic diagram of the test cell.

As clearly shown in Figure 6a, the field distribution in the hemispherical cell and the determination of E_c relies on the accurate determination of the voltage level at which the second current peak starts to appear. After this, use of the numerically or analytically computed field at the active electrode for this 'critical' voltage yields the threshold field E_c. Therefore, the accuracy of such procedure is not expected to be extremely high. For this reason, an alternative test was developed which allows a better accuracy. To achieve this, a test cell with a uniform field distribution was designed. In this case, when the ionisation level is reached, instantaneous breakdown follows. Therefore, a measurement of the breakdown voltage should yield a more accurate value for the ionisation threshold electric field, E_c.

The parallel plate was filled with wet sand and subjected to positive impulses with increasing voltage levels. Up-and-down tests according to procedures specified by IEC-60 [10] were conducted to estimate the breakdown threshold voltage of sand with different percentage of water contents.

3.3.1 Parallel Plate Test Cell

The test circuit arrangement and transducers adopted were similar to the work with the hemispherical cell. Figure 7 shows the construction of the parallel plate adopted in this test designed essentially for characterisation tests at low voltages and variable frequency tests [15]. This parallel plate, which provides a uniform electric field is designed to BS 1377 recommendations [16] 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 sand in order to minimise sharp edges and air gaps which might exist in soil particles and between the beam electrode and the test medium.

3.3.2 Cell Calibration with Air

In order to check the uniformity of the field in the parallel plate test cell and to show that the breakdown voltage is not greatly affected by localised abnormalities in the test cell electrode surfaces, impulse tests were first conducted on the parallel plate separated by an air gap of 1cm. Impulse tests were carried out with increasing voltage magnitudes under both positive and negative polarities, and it was verified that no conduction current was measurable under these conditions. However, during breakdown, a sudden rise in current or voltage drop was observed. E_{50} was measured to be 26kV/cm for positive polarity and 28kV/cm for negative polarity. These values are close to the results found in the literature [17] for impulse air breakdown in uniform field. It could therefore be assumed that the parallel plate adopted has the required uniform field distribution necessary to determine the soil ionisation/breakdown characteristics.

3.3.3 Sand Impulse Resistance in Uniform Field

Impulse tests were conducted using the parallel plate test cell filled with 1cm, 2cm, 3cm and 4cm thick of wet sand. Sand with 1%, 3%, 5%, 7% and 10% water contents were used as the test media. The breakdown electric field with the various test media was found to be independent of soil thickness. In this study, the results of 1cm thick of wet sand between the parallel plate were presented. Voltage and current traces for sand with different water contents were recorded with increasing charging voltages of the impulse generator. Initial oscillations were observed, and they are attributed to capacitive effects. With higher percentages of water content inside the sand, less oscillation was observed.

As predicted, because of the uniform field condition in the test cell, no second current peak was observed for all voltages until the breakdown level. Another factor that could affect this observation is the small spacing between the parallel plates, giving ionisation propagation times so small that they could not be detected with the present transducers. The measurements showed that the resistance value (measured as $\frac{V\,at\,I_{peak}}{I_{peak}}$) decreased with increasing current magnitudes (Figure 8) which can be explained by thermal effects enhancing ionic conduction. Although the resistance was measured before the ionisation process takes place in the test media, the resistance/resisitivity values were found to be lower than those obtained with DC or AC tests, as determined by a parallel investigation by Srisakot et al. [15]. This is thought to be caused by thermal effects, but water settling processes in the test cell could also contribute to this non-linear behaviour of the test soils.

3.3.4 Soil Ionisation Threshold Electric Field (E_c)

Ideally, sand should be replaced with a new test sample for each shot as it is not a self-restoring material. However, after completing the tests, a few holes of different sizes within 0.5cm-diameter and 1cm depth were observed on the surface of the sand. The number of holes was found to be equal to the number of breakdowns which indicated that ionisation had taken place for each breakdown. This is not surprising since the field enhancement process will encourage initiation of discharges in the sand. This makes the apparent dielectric strength of the sand medium lower than the air channel formed by the previous breakdown.

This breakdown electric field, which in this case corresponds to the sand ionisation threshold, was found to be independent of the sand water content and had an average of 7.9kV/cm under positive impulse. This E_c value is found to be lower than the breakdown strength of air (see section 3.3.2). This finding is similar to the results obtained by Cabrera et al [4] for soil resistivity of less than 100kΩm. It should also be emphasized that the E_c obtained with the parallel plate cell is higher than the threshold electric field obtained with the hemispherical configuration (E_c of 5.5kV/cm.

The smaller dimensions of the parallel plate test cell and the small amount of wet sand used during each test had less effects on drying, heating and water settling processes in sand compared with the larger hemispherical test cell. Moreover, as expected, the breakdown, hence, soil ionisation threshold electric field was found to be higher under negative polarity with an average of 9kV/cm for all samples than the positive value of 7.9kV/cm. This difference is comparable to that measured with the hemispherical container (see section 3.1.2). These differences in soil characteristics corresponding to different impulse polarities reinforced the assumption that non-linear soil behaviour is attributed to a soil ionisation process.

3.3.5 Time Lag of Soil Ionisation

When the time to breakdown (t_B) which was measured from a virtual origin to the time at which a sudden rise in current or voltage drop was observed, t_B was found to be lower in high conductivity sands and decreased with increasing breakdown voltage. Also, t_B in negative polarity was found to be higher than in positive impulses. Figure 9 shows the breakdown voltage, V_B versus time to breakdown t_B for sand with 1% and 5% of water content under both impulse polarities.

The t_B values also showed a statistical variation when tests were.

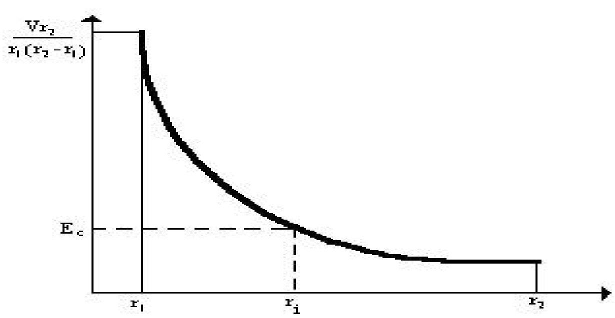


Figure 6a: Electric field distribution in the hemispherical test cell.

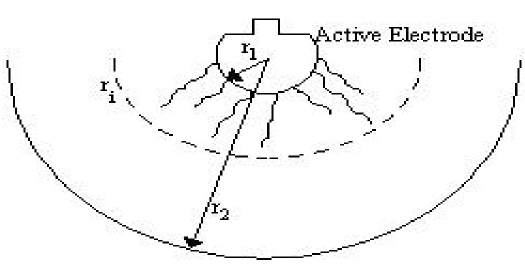
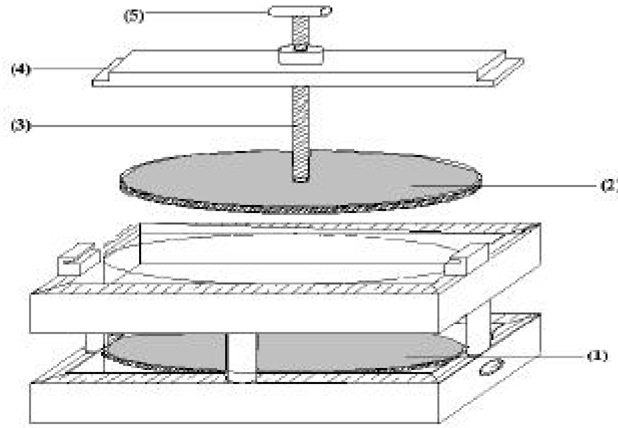


Figure 6b: Schematic diagram of the hemispherical test rig with the ionisation process.



(1) Lower electrode; (2) Top electrode;
(3) Adjustment rod; (4) Latching beam; (5) Handle

Figure 7: A schematic diagram of the parallel plate test cell.

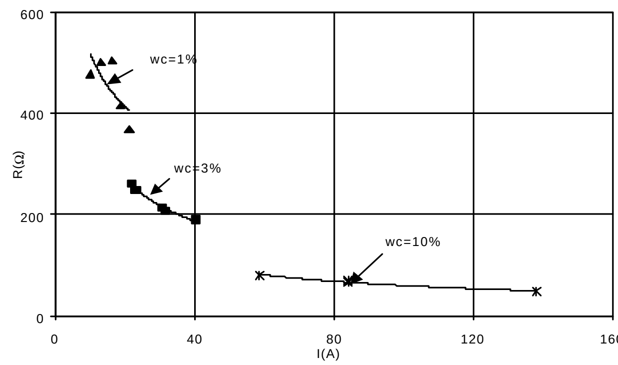


Figure 8: Resistance vs current magnitudes of parallel plate filled with sand of different water contents.

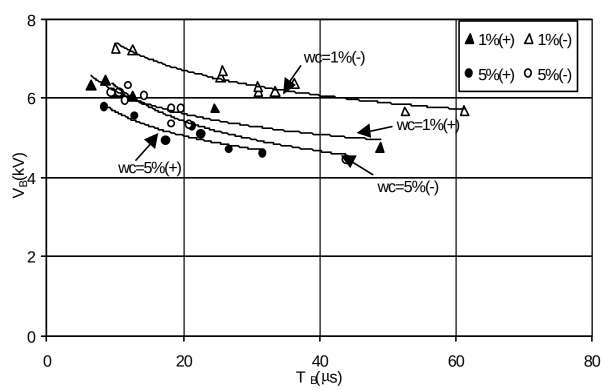


Figure 9: Breakdown voltage vs time-to-breakdown for sand with 1% and 5% water content positive and negative polarity impulses.

4. CONCLUSION

The effects of impulse polarity, soil grain size and the threshold level on the electrical properties of soil under fast impulses were investigated. It was found that the pre-ionisation and post-ionisation resistances, R_1 and R_2 and the ionisation threshold electric field, E_c, is higher under negative impulse for soils with different water contents. This observation was explained by the breakdown characteristics of the air pockets trapped within the soil. In addition, it was found that the process of ionisation under negative impulse exhibited longer times-to-initiation, and slower rates of propagation once the ionisation process has started.

In addition, it was observed that the medium grain size had lower pre-ionisation and post-ionisation resistance values for a given applied voltage and water content. However, the grain size did not affect the threshold electric field above which ionisation was initiated.

Using a parallel plate test cell, a mere measurement of breakdown voltage will give a more accurate estimation of the threshold field. This is because as soon as ionisation is initiated, instantaneous breakdown follows. Values of 9kV/cm and 7.9kV/cm were measured for negative and positive polarities respectively.

It should be noted that these values are higher than those determined earlier with the hemispherical test cell. This is thought to be caused by the non-uniform field distribution in the latter case which encourages ionisation to develop quickly. Moreover, using the parallel plate test cell, it was found that breakdown always occurred through the soil despite the existence of an 'air channel' through which previous breakdown occurred. This indicates that the dielectric strength of the soil was lower than that of air for all water contents. This evidence was confirmed by observing the breakdown channels through each series of tests.

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