THE DIELECTRIC CONSTANT AS A MEANS OF ASSESSING THE PROPERTIES OF ROAD CONSTRUCTION MATERIALS

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ABSTRACT

Recent experience with a number of material-related construction problems has indicated that many of the fundamental chemical and chemico-physical properties of these materials are not clearly understood. These are related for instance to the hydrophilic/hydrophobic properties, surface charges, ionic bonding, zeta potential and dielectric constant of the materials. These appear to affect the water susceptibility and stabilization potential of the materials. One particular area of interest in the United States is the use of the dielectric properties of soils and stabilized materials in the prediction of their performance when used in road pavements. The relevance of the dielectric constant (DC) as a road construction material assessment and quality control parameter has, however, not been clearly demonstrated and some fundamental research in this area has been undertaken. The results of testing a range of materials under different conditions are presented and demonstrate the measurement of the DC to be primarily relevant for moisture content assessment at constant density or vice versa. This renders DC measurements useful only for limited applications and where one variable remains constant. Critical discussion regarding the possible use of the DC in South Africa is presented.

1 INTRODUCTION

Recent experience with a number of material-related construction problems has indicated that many fundamental and chemico-physical properties of these materials are not clearly understood. These are related for instance to the hydrophilic/hydrophobic properties, surface charges, ionic bonding, zeta potential, dielectric constant, etc, of the materials, many of which react erratically with water and soil stabilizers (bituminous and hydraulic). One particular field that is gaining momentum in the United States, particularly, is the use of the dielectric properties of soils and stabilized materials in the prediction of their performance when used in road pavements. The Tube Suction Test (TST) (Hilbrich & Scullion, 2008) in particular, is being increasingly used to predict the “durability” of stabilized materials in the United States. The relevance of the dielectric constant (DC) as a road construction material assessment and quality control parameter has, however, not been clearly demonstrated and some fundamental research in this area has been undertaken.

The aim of the current work was to determine the influence of various fundamental material properties that affect the performance of materials when used in road construction and their effect on the dielectric constant of materials. The investigation entailed preliminary testing of a range of materials under different moisture and density conditions to evaluate the variation in DC of local materials.

2 BACKGROUND

The dielectric properties of a material are essentially a measure of the capability of the material to act as an electrical insulator, or a measure of the electric permittivity (electrical conductivity) of the material, i.e., the ability of the material to allow the flow of electrical current through it. The materials may hold an electrostatic charge but this charge may not necessarily flow, although the electrostatic lines of flux are not impeded or interrupted. Essentially, dielectric materials have no loosely bound or free electrons to conduct a current and by definition a dielectric material is one that has a low permittivity (i.e., is an insulator). The dielectric constant is thus a measure of a material's insulating capacity or that property of a dielectric which determines the electrostatic energy stored per unit volume for unit potential gradient. It is also a measure of a substance's relative hydrophilic character.

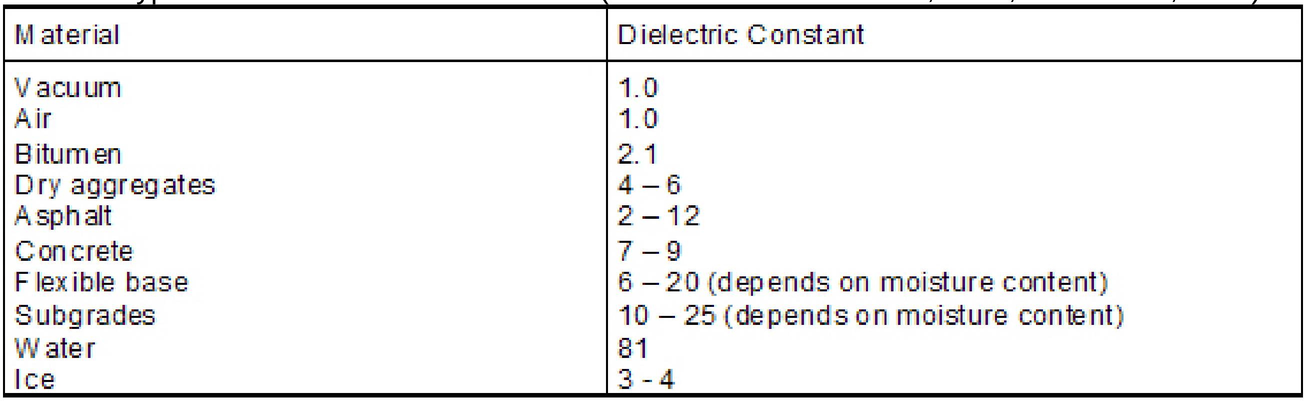
The dielectric constant of a material is equal to the ratio of the electrostatic capacity of condenser plates separated by the material to that of the same condenser with a vacuum (assigned a value of 1.0) between the plates (Scullion and Saarenketo, 1997).

The dielectric constant of a soil-water-air mixture is a function of:

- dielectric constants of the individual components;
- volume fractions of the components;
- geometric properties of the components; and
- electrochemical interactions between the components (Saarenketo, 1998).

Typical values of the Dielectric Constant for highway materials are shown in Table 1.

Table 1: Typical values of Dielectric Constant (Scullion and Saarenketo, 1997; Evans et al, 2007)



Material	Dielectric Constant
Vacuum	1.0
Air	1.0
Bitumen	2.1
Dry aggregates	4 – 6
Asphalt	2 – 12
Concrete	7 – 9
Flexible base	6 – 20 (depends on moisture content)
Subgrades	10 – 25 (depends on moisture content)
Water	81
Ice	3 - 4

The Dielectric Constant is measured using equipment based on Time Domain Reflectometry (TDR) principles. The equipment consists of a surface probe (more like a contact foot) and a display unit (Figure 1). A 1.36 kg weight is used to ensure consistent pressure during measurement. A Rainbow Instrument Dielectric Sensor was used for all DC measurements in this study.

The sensor consists of a transmitter and receiver integrated into the probe and the probe sweep scans a certain frequency band to find the resonant frequency. The dielectric constant of the material is inversely proportional to the resonant frequency. The probe has a depth of penetration into the materials to be measured of about (25 to 50 mm) depending on the material.

Figure 1: The Rainbow Instruments Dielectric Sensor. Measuring unit, probe with 3lb weight placed on the Perspex block used to regulate the sensor**.**

3 EXPERIMENTAL WORK

In order to get a fundamental understanding of the dielectric properties of materials, a range of materials was tested using the sensor. The testing was carried out in 3 stages during an ongoing research project.

3.1 Stage One

The first stage involved testing samples covering a range of properties from highly active clays to clean sands. The samples were compacted at 95% of the Mod AASHTO maximum dry density at optimum moisture content (OMC) and then allowed to dry with periodic DC measurements. The moisture contents and density condition were known factors during testing. Each dielectric measurement for analysis was taken as the average of four measurements taken on various positions on the surface of the sample as illustrated in Figure 2.

Tests were also carried out to determine the effect of stabilizers on the dielectric constant of materials. Three specimens each of untreated black clay and black clay treated with 5% lime were moulded and then allowed to dry back at ambient conditions for several days until the dielectric values stabilised. The samples were then subjected to a modified Tube Suction Test. The Tube Suction Test is based on the change in dielectric constant of a 300 x 150 mm compacted stabilized specimen with increased capillary suction from the base of the specimen over a 10 day period. The test essentially determines the rate of capillary suction in the specimen based on the unbound water content. The objective of this test was to predict the permanency (durability) of stabilized layers (Hilbrich and Scullion, 2008).

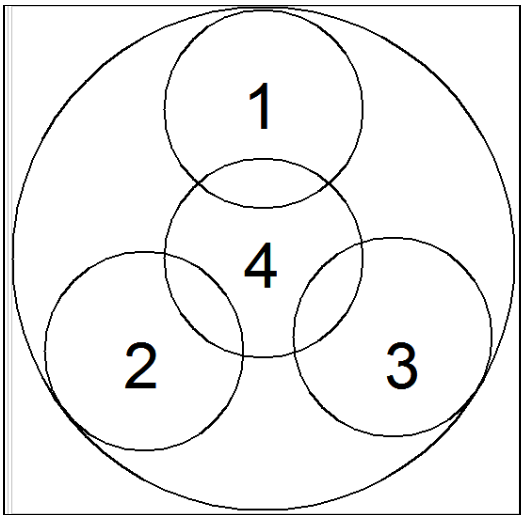


Figure 2: Measuring points on the surface of the sample.

3.2 Stage Two

The second stage of the study was carried out to determine if any additional factors affect the DC readings of materials. The factors that were investigated were water quality and density. The correction of DC readings according to temperature was also investigated.

3.2.1 Correlation between DC and temperature

Since the temperature of a material has an effect on the DC of the material, all DC readings should be corrected to a reference temperature before evaluating the readings. For this reason the DC of the Perspex block supplied with the Rainbow Instruments dielectric probe for calibration was measured at various temperatures to determine the manner and the rate at which the DC changes occur with temperature. As different materials may exhibit different rates of change of DC with changes in temperature the DC of a core of anorthosite and three asphalt cores were also measured to observe if the material had a similar rate and pattern of DC change to the Perspex block.

3.2.2 Effect of water quality on DC

In order to determine the effect of water quality on the dielectric constant a single material was compacted using water with different salt contents. The aim of this experiment was to determine the effect that different construction water qualities would have on DC readings taken during construction and the effect of different quality infiltration waters on DC readings of completed pavements. The tested samples were compacted at constant moisture content and under the same compactive effort. The salt content of the water varied from 0g/l NaCl (distilled water) to 20g/l NaCl in order to cover the full range of water classes as defined by the South African National standards water classes and extreme cases of salt concentrations (20g/l).

3.2.3 Field readings on road

As an initial investigation of the feasibility of using the DC as a measure of the changing moisture conditions within a pavement structure, a section of existing road was monitored on the CSIR campus. The road section selected was extensively cracked on the one edge while the other areas were intact (Figure 3). Monitoring involved the measurement of the DC of the road at specific points laterally across the road.

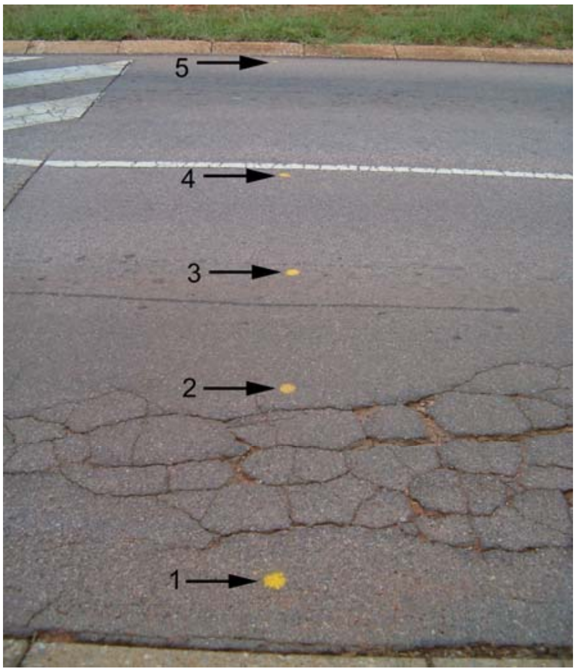


Figure 3: Road section tested showing position of measuring points and extensive cracking between points 1 and 2.

The DC was measured on four different occasions during the study period as the moisture conditions of the road were expected to change due to the onset of the rainy season. No material samples were taken and as such no gravimetric moisture content evaluations were done. The area closest to the crack (Sample point 1) was assumed to have been exposed to infiltrating water and as such was expected to have a higher moisture content.

The experiment was therefore not a quantitative investigation of DC versus moisture content but rather a qualitative investigation of relative changes in DC readings with changing moisture conditions. As the road is old (constructed in approximately 1970) and lightly trafficked no compaction of the pavement layers is expected to have occurred during the monitoring period. Any changes in DC values would therefore be due solely to changing temperatures or moisture conditions.

3.2.4 DC versus density

Various materials were compacted in standard CBR moulds at various moisture contents and to various densities. The purpose of the process was to determine if the different materials show any different trends of DC with varying moisture contents and density.

3.3 Stage Three

During the third and final stage the effects of both moisture content and density on DC readings of untreated materials was further investigated. DC measurements of compacted samples of known moisture content and density were recorded to analyse the relationship between the factors. Three materials were selected and used for DC measurements after the routine compaction tests were carried out to determine OMC and maximum dry density of each material. Of the three materials, a total of 87 samples (61 from material A, 16 from material B and 10 from material C) were compacted for correlation analysis. The investigation also took into account the use of a temperature correction factor as specified in previous testing.

Routine compaction tests with varying moisture contents and density were carried out on moulds of material A and B with the dielectric measurements being taken on each mould. Material C moulds were compacted at a constant moisture content to varying densities to determine the effect of density alone on the DC of a sample. A regression analysis was also performed on the results to evaluate the relationship between the three factors and to evaluate which factor (moisture content or density) had a more significant affect on the DC.

4 RESULTS AND DISCUSSION

4.1 Stage One

The relationship between the DC and moisture content of the materials compacted to maximum dry density showed that, for the sand, no correlation can be made between dielectric constant and moisture content. For all other materials an increase in DC with increasing moisture content was observed (Figure 4). The relationship of the dielectric constant of the materials compacted at OMC to densities ranging from 90 to 100% of max dry density revealed similar trends of DC increasing with density (Figure 5).

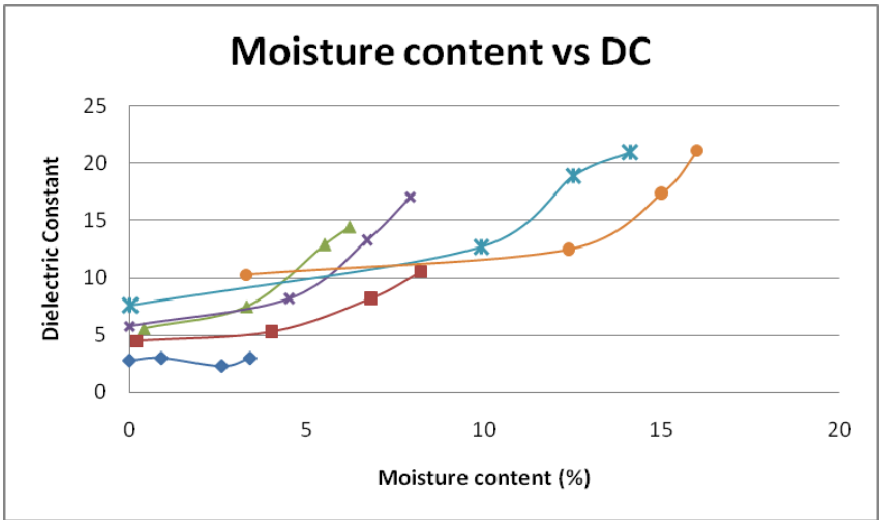


Figure 4: Moisture content vs dielectric constant for different materials

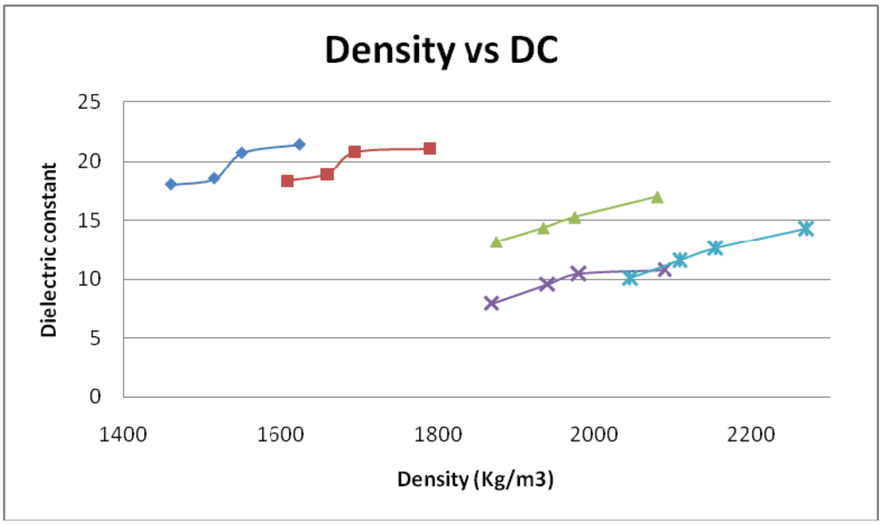


Figure 5: Relationship between density and Dielectric Constant for various materials

The Tube Suction Test (TST) investigation into the effect of stabilization showed that the top of the sample appears to have dried out over the first 12 days (Figure 6), before the suction effects brought moisture into the area of influence of the test probe. Thereafter the dielectric constant was directly affected by the increasing moisture content. The same pattern was obtained for both the stabilized and unstabilized materials, although the effect of the stabilization appeared to reduce the water content slightly (Figure 6). This investigation, however, did not reveal significant results and as such needs to be explored further.

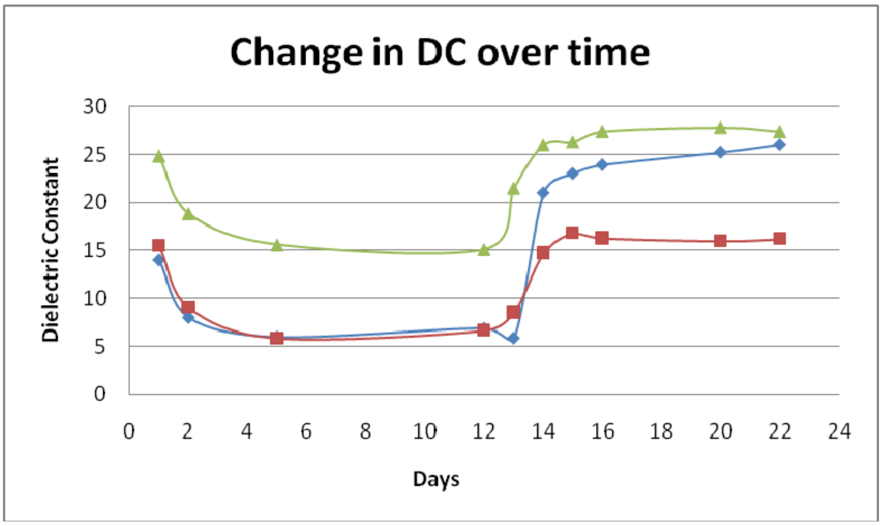


Figure 6: Change of dielectric constant with time for untreated and stabilized materials in tube suction test

4.2 Stage two

The observed relationship of changing DC with changing temperature (Figure 7) of all tested materials revealed a definite positive correlation between increasing temperature and DC. The effect of temperature on the DC was, however, highly variable but not extreme with gradients of the linear trends not exceeding 0.07. Temperature corrections should, however, be applied and for consistency a conservative correction gradient of 0.05 was used in all subsequent tests. It is believed to be important to apply a means of correction as significant variance in DC values may otherwise be lost (or added) especially when materials are tested with a high temperature range.

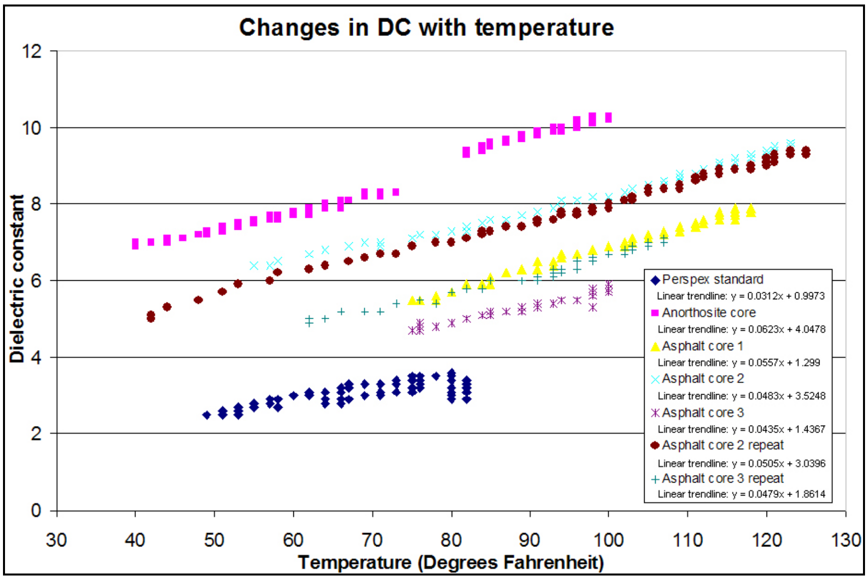


Figure 7: Plot illustrating the changes in DC with Temperature

The DC of the material does not follow any specific trend with increasing moisture salt content (Table 2) and therefore the quality of the water used during construction or the quality of water infiltrating a completed pavement will most probably not have a significant effect on the DC readings. It must be mentioned that only the salt content of the water was varied and it can therefore be concluded that salt concentrations (NaCl and similar) do not appear to affect the DC of materials. Other forms of pollution, e.g. metals and non aqueous phase liquids, could affect the DC.

The measurement of the DC of an existing road revealed that the DC sensor could not detect changes in moisture content in materials under a layer of asphalt. A possible source of error associated with the experiment is that the sensor has a reported maximum depth of penetration of 5cm. The asphalt and reseal on the tested road section may approach this thickness and as such the readings would only indicate the DC of the relatively hydrophobic asphalt layer. Based on stage two results the suitability of the DC sensor as a density determining device for compacted materials seems limited as no consistent trend was observed within the limited samples set tested.

Table 2: Summary of properties of the samples used to determine the effect of salt water on DC readings.

Sample Number	Water Salt content (g/l NaCl)	Soil Moisture content (%)	Soil Density (g/ml)	Dry density (g/ml)	Dielectric constant
1	0	7.65	1.87	1.73	12.025
2	0.5	7.76	1.86	1.72	10.65
3	1	7.52	1.87	1.74	12.15
4	2	7.70	1.82	1.69	10.925
5	10	7.66	1.85	1.72	11.95
6	20	7.48	1.86	1.74	11.925

4.3 Stage Three

4.3.1 Laboratory analysis

The relationships between the DC, moisture content and density obtained for all samples from the three materials tested are illustrated in Figure 8 to Figure 11.

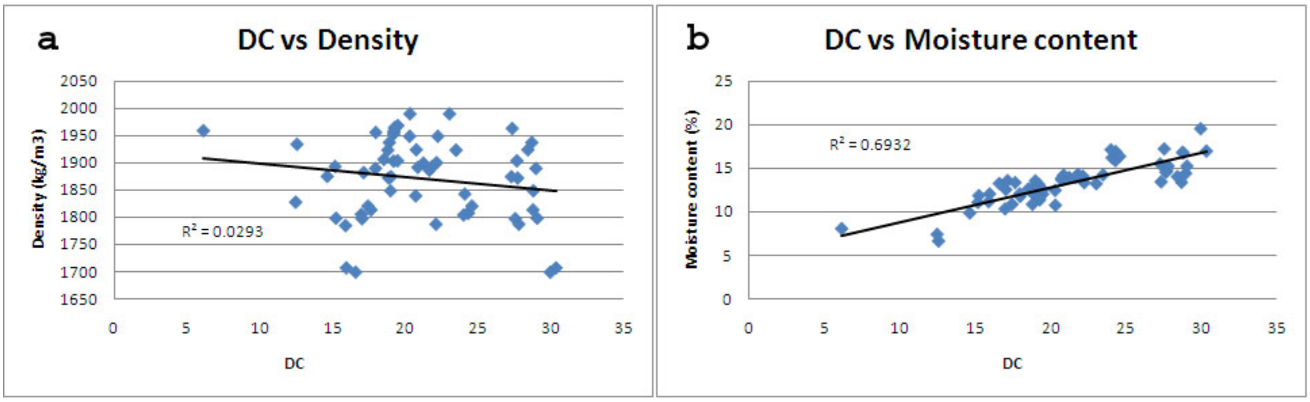


Figure 8: The distribution of DC readings in relation to a: density and b: moisture content (Material A with 61 values in data set)

The results for material A and B show that no significant relationship exists between density and DC since the regression coefficients are 0.03 and 0.27 respectively (Figure 8a and Figure 9a). The relationship between the moisture content and DC is better with regression coefficients of 0.69 and 0.73 respectively (Figure 7b and 8b).

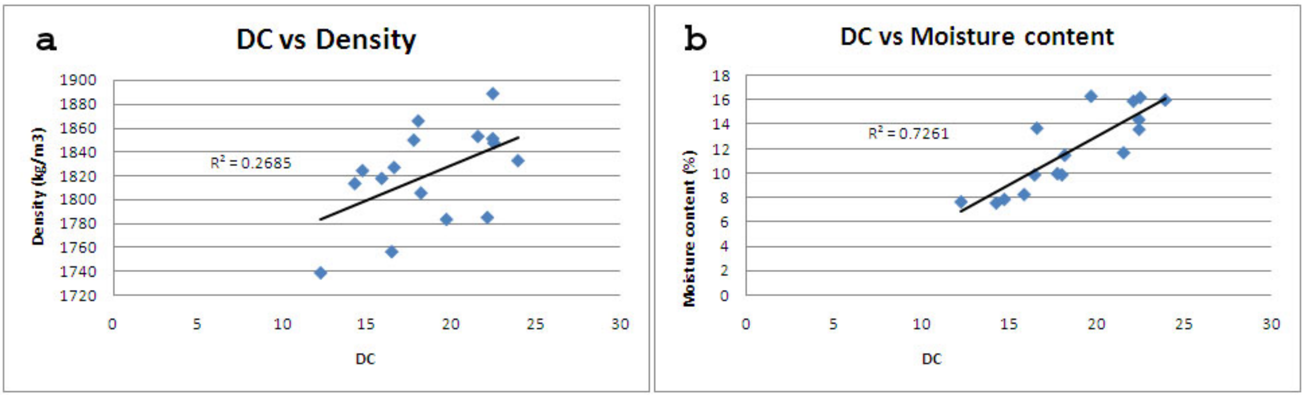


Figure 9: The distribution of DC readings in relation to A: density and B: moisture content (Material B with 16 values in data set)

Since the moisture content of the material appeared to have a significant effect on the DC of the specimens and the density had little or no effect, an experiment was carried out to determine whether the density would affect the DC without any variation in the moisture content. Samples that were compacted for CBR testing (material A), with constant moisture content but different densities, were used for DC measurements

The data set consisted of 5 sets of 3 moulds of compacted soil at optimum moisture content, and varying densities. DC measurements were also taken after the standard four day soaking period to evaluate the changes in moisture content and its effect on the DC-density relationship. The results are plotted in Figure 10a and b.

When material A samples were compacted to various densities at constant moisture content (three repetitive samples) the DC of the samples increased with an increase in density (Figure 10a). The regression coefficient for this relationship ranged from 0.93 to 0.99 (average of 0.965).

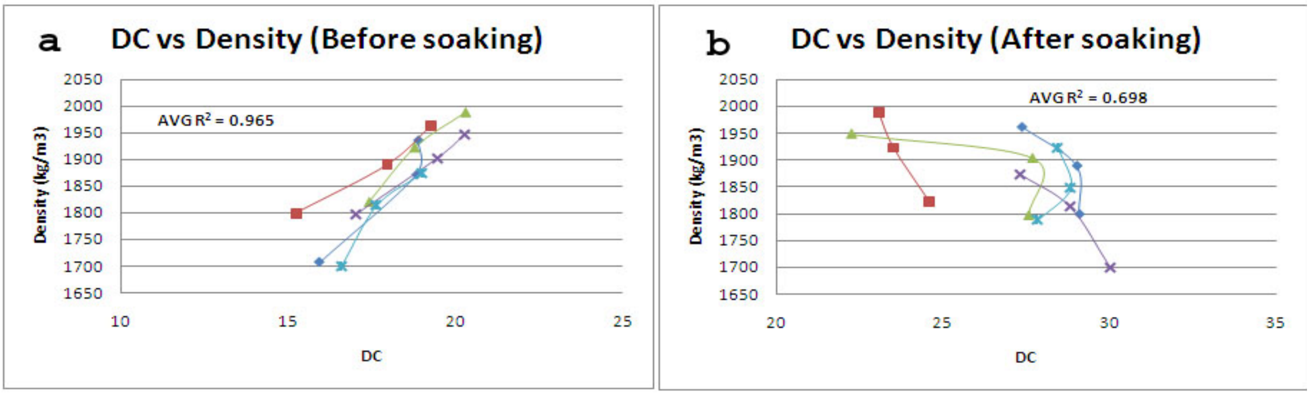


Figure 10: The relationship between DC and density before (a) and after (b) soaking (Material C with 10 values in the data set)

The relationship changes when the samples are soaked for the standard four day period and the moisture contents increased from initial values of between 11 and 13% to from 13 to 19% after soaking. The highly variable changes in moisture content resulted in an erratic effect on the DC (Figure 10b) with the DC to density regression coefficient ranging from 0.32 to 0.98. This again illustrates the greater significance of moisture content than density on the DC.

When material C was used to extend the investigation of the effect of density on the DC two sets of 5 moulds were compacted at constant moisture content with 5 different compactive efforts. In this case the stronger relationship is observed to be between DC and density (Figure 11a) than between moisture content and DC.

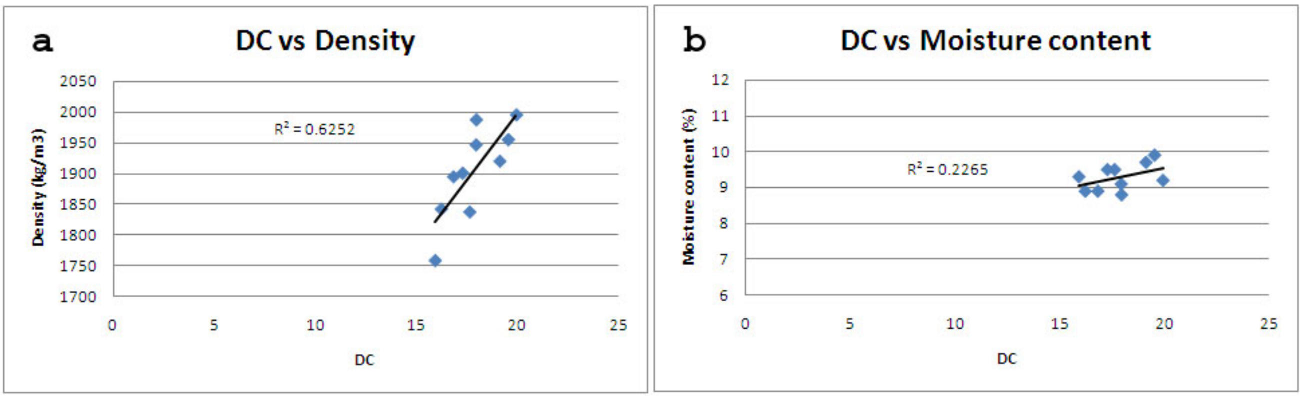


Figure 11: The distribution of DC readings in relation to a: density and b: moisture content (material C with 10 values in data set)

4.3.2 Regression Analysis

The data set was run through a regression analysis to confirm the results obtained from laboratory testing. A linear regression analysis is performed by using the "least squares" method to fit a line through a set of observations. It can be used to analyze how a single dependent variable is affected by the values of one or more independent variables. In this case the analysis is carried out to determine how the DC is affected by the other two factors (moisture content and density). Contributions in the performance measure can then be allocated to each of the factors, based on the performance data.

In general, the equation of a line is written as:

$$Y = a + b * X \qquad (1)$$

Where Y is the dependent variable, X is the independent variable, a is the intercept and b is the coefficient of change on X (b measures how much Y changes when X changes by 1). Once the regression analysis is run, estimated coefficients of change associated with each of the X variables will be calculated and the output can then be written in the form of the general equation (1). The coefficients describe the size of the effect the independent variables (X_1, X_2, X_3) have on the dependent variable Y, and a is the value Y is predicted to have when all the independent variables are equal to zero.

The regression analysis showed moisture content to have a more significant effect on DC than density. Density data was then discarded and the regression analysis run again to verify the coefficients obtained before. From both analyses run, the coefficients obtained for moisture content were 1.06 and 1.03, which was significantly higher than that of density. The coefficient obtained for density was 0.0068. The R-squared valued obtained for both analyses was 0.69, which is similar to the values obtained in the previous analyses.

5 SUMMARY

Despite the effect of temperature on the DC being very small a consistent conservative correction gradient of 0.05 was used in this research. It was shown that DC is not affected by change in water quality but only the effects of NaCl were investigated and as such some very dense pollutants or pollutants other than common salts could have an effect on the DC of materials. Generally such pollutants are uncommon in infiltration and construction waters and it therefore seems unlikely that DC measurements are significantly affected by water quality.

The testing of an existing road proved inconclusive since the dielectric sensor appears to only measure the top 5 cm of a layer. The sensor is thus probably not suitable for investigating pavements below a depth of 5cm.

The suitability of the Dielectric constant for monitoring and controlling the density of compacted materials seems limited as there are many variables that affect the readings. Laboratory investigations under controlled conditions (constant moisture and temperature) may possibly yield some useful results but this may not provide good correlations for field investigations.

The DC sensor may be useful as a tool to measure the moisture content of a material. Even with varying densities, moisture content has a significant effect on the DC of a material. This does not hold true for density. The dielectric sensor is based on Time Domain Reflectometry (TDR), which determines the dielectric permittivity of a medium by measuring the time it takes for an electromagnetic wave to propagate along a transmission line that is surrounded by the medium. (In fact, TDR is a standard process for measuring moisture content in soils and agricultural produce.)The transit time (*t*) for an electromagnetic pulse to travel the length of a transmission line and return is related to the dielectric permittivity of the medium. The permittivity is the property of the dielectric that determines how well it transmits an electric field (Wacker, 2002).

For the samples tested, the transmission line would refer to the soil, water and air that fill the voids in the soil. The electromagnetic wave is likely to follow the easiest path, which is through the water in the voids. Hence, an increase in the moisture content would result in an increase in the DC of the material. For those samples with constant moisture content and varying densities, the same principle would apply. As the density increases, the void spaces decrease, thereby causing the water molecules to accumulate and form easy “pathways” for the electromagnetic waves. This would result in higher DC values.

This is verified in the work by Saarenketo (1998), in which the degree of compaction is demonstrated to have a considerable effect on the dielectric of a material. The air component within the sample is reduced for a higher compaction effort and for a fixed moisture content the saturation ratio in the voids would increase, resulting in a higher dielectric value. The dielectric constant is significantly affected by the moisture content of a material, which in turn is a function of the density and void ratio of that material. Although used as an indicator of the durability of stabilized materials in the United States, the dielectric constant does not appear to be useful for this purpose in South Africa. Durability is related to the ability of the material to resist deterioration under external forces. Although excessive moisture can weaken materials, it does not necessarily indicate that the material is non-durable.

6 CONCLUSION

The general outcome of the study shows that the dielectric sensor may be useful as a tool to measure the moisture content of a material and this may, for example, be useful to test the amount of moisture infiltration through a pavement seal by monitoring the change in moisture content of the upper part of a base course with time. However for deeper moisture content measurements the DC sensor will be impractical for routine measurements as it will require the creation of an access pit to reach the deeper layers.

Another use of the DC that may be feasible is that of determining the density of material that has a known constant moisture content. An example of such an application would be the measurement of DC (and the subsequent derivation of the density) of various points across a recently constructed pavement layer, bearing in mind that it is probably only the upper 50 mm of the layer that is being evaluated.

However as a general material characterizing tool the DC sensor appears to be of limited use since too many variables affect it and extensive calibration is needed. The use of the DC as an indication of stabilization durability and pavement design as applied in the USA appears to be very tenuous and results from this study show that the dielectric sensor primarily measures the water content in a material. The presence of water, however, in stabilized materials is not necessarily an indication of potential durability. Durability is related to the ability of the material to resist deterioration under external forces. Although excessive moisture can weaken materials, it does not necessarily indicate that the material is non-durable.

7 ACKNOWLEDGEMENTS

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