Applications of Dielectric Constant Measurements in Geotechnical Engineering

by

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Introduction

The importance of the study of soil behaviour is well recognised and many efforts have been made in relation to various geotechnical investigations. It is shown that the engineering behaviour of a soil is determined by the soil structure, which is influenced by the interaction of composition and environment. Some of the important compositional properties include particle size distribution, mineralogical and chemical composition, colloidal properties etc., while the environment includes factors such as stress and geological history, water content, orientation and temperature.

Unfortunately, the different means devised for soil investigations involve time consuming and complex techniques, expensive apparatus and require the skill of experienced technicians. While the simpler methods available are often satisfactory for routine purposes, they are either arbitrary or inadequate as a basis for predicting the soil behaviour. Further, they do not consider the interaction of compositional properties and environmental factors.

Mitchell and Arulanandan (1968) indicated that the electrical properties of soil could be used to characterise both the compositional and environmental parameters to predict the engineering behaviour of soils. Chauhan (1982), Chauhan and Kate (1983), Kate (1979), and Malhotra (1979) have utilised electrical resistivity measurements as applied to geotechnical investigation.

The main objective of this paper is to describe some studies on the potential applications of the dielectric constant measurements to characterise soils and predict their basic behaviour. The paper shows the results of some standard laboratory tests carried out on various types and proportions of sand-clay mixtures. These results are quantified and correlated with the corresponding dielectric constant measurements.

Scope of the Study

Based on the electrical response characteristics of soils, a new approach for geotechnical investigations is proposed. An experimental method to

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measure the dielectric constant of a clay-water-electrolyte system is described and the significance of measurements is explained. Some applications of dielectric constant measurements described in this paper are as follows :

1. Determination of cation exchange capacity

2. Determination of expansion index

3. Identification of dispersants and flocculants

4. Identification and classification of soils

5. Soil stabilisation.

Dielectric Constant of Clay-water-Electrolyte Systems

When an impulse of alternating current is applied to a clay-water-electrolyte system, its response can be measured in terms of a resistance (R) and a capacitance (C). The measured value of the capacitance (C) can be expressed in terms of the dielectric constant ϵ of the medium. The dielectric constant (ϵ) is defined as the ratio of the measured capacitance to the capacitance measured when there is only a vacuum between the electrodes. The measured value of the dielectric constant of a clay-water-electrolyte system in the radio frequency range of 10^6 to 10^8 Hz is usually referred to as the 'apparent dielectric constant' (ϵ'). From a knowledge of the dimensions of the sample, the dielectric constant (ϵ') and the conductivity (σ) can be calculated by using the following relationships :

$$\epsilon' = \frac{Cd}{A\epsilon_0} \qquad\qquad ...(1)$$

$$\sigma = \frac{d}{RA} \qquad\qquad ...(2)$$

where d= the length of the sample,

A= cross-sectional area,

ϵ_o= the dielectric constant of vacuum
   (8.85×10^{-14} farad cm^{-1})

It has been shown (Arulanandan and Smith, 1973) that the dielectric constant is a function of the frequency of the alternating current. The difference in the constant measured at a frequency of 3×10^6 Hz and that measured at 75×10^6 Hz is generally defined as the magnitude of dielectric dispersion ($\triangle\epsilon'$) (Fernando et. al., 1977). A typical plot of apparent dielectric constant (ϵ') versus frequency (f) and the associated magnitude of dielectric dispersion ($\triangle\epsilon'$) is shown in Figure 1 for montmorillonite, illite and kaolinite. The magnitude of dielectric dispersion ($\triangle\epsilon'$) is shown (Arulanandan, 1973) to be a function of clay mineral composition, clay content, water content, cation type, porefluid concentration, structure, and particle orientation. The dependance of $\triangle\epsilon'$ on these factors is shown in Table I. Because these factors have a profound influence on soil behaviour, the magnitude of dielectric dispersion ($\triangle\epsilon'$) is considered to be a potential electrical property that can be used in understanding the basic soil behaviour.
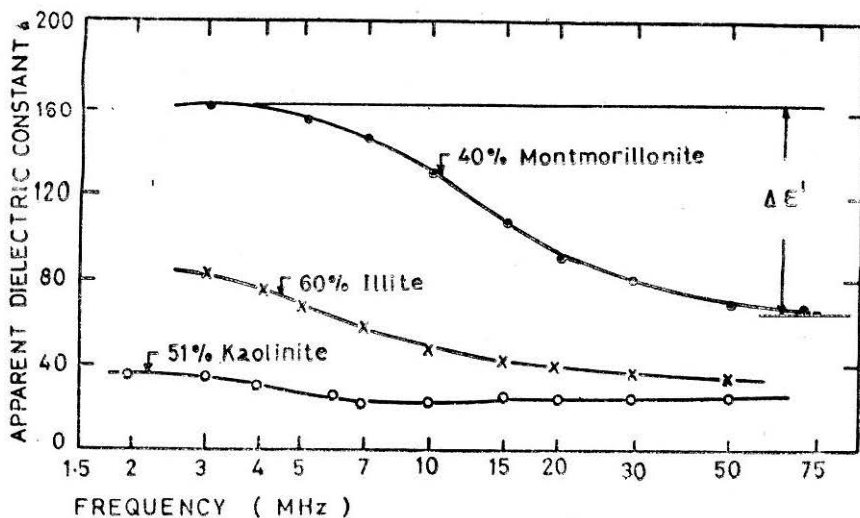
FIGURE 1 Electrical Dispersion of Different Types of Sandclay Mixtures.

TABLE I Influence of Soil Parameters on Dielectric Dispersion

Factor	Effect
Type of clay	$\triangle\epsilon'$ is different for clay types, it increases in the following order : Montmorillonite, Illite, Kaolinite.
Clay content	$\triangle\epsilon'$ increases significantly with increasing clay content.
Water content	$\triangle\epsilon'$ is not affected by the water content in the radio frequency range.
Cation type	$\triangle\epsilon'$ increases slightly with increasing Sodium Adsorption Ratio (SAR)*
Electrolyte concentration	$\triangle\epsilon'$ decreases slightly with increasing electrolyte concentration.
Structure	$\triangle\epsilon'$ increases slightly to moderately with increasing dispersion of particles.
Particle orientation	$\triangle\epsilon'$ is higher when current is flowing perpendicular to the direction of consolidation pressure than when current is flowing parallel to the direction of consolidation pressure.

* $SAR = (Na^+)/[^1/_2 (Ca^{++}+Mg^{++})]^{1/_2}$.

Experimental Studies

a. Soils studied : Eleven natural soils having different sand-clay proportions and types of clay obtained from various parts of the State of California, U. S. A., were studied to examine the potential of the magnitude of dielectric dispersion and establish its relationship with various soil properties. The mineralogical composition and properties of these soils are given in Table 2.

TABLE 2 Composition and Properties of Soil Samples

Mineral or sample property	Soil Sample Number										
	1	2	3	4	5	6	7	8	9	10	11
Quartz	35	25-30	25	25	35	25	35-40	25	35	25	20
Mixture of mixed layer clay and mont-morillonite					25						30
Chlorite	5		5	5	<5		5		5	<5	
Mica	5		<5	5	<5		<5	5	<5	5	
Iron oxide	5	5	5	5	<5	<5		<5	<5		<5
Mixed layer clays	10			15-20			25-30		15		
Iron sulphide				5	<5			5			
Montmorillonite		30	>30			>30		15-20		>30	
Kaolinite		5									
Halloysite								5-10			
Per cent passing 75-micron sieve	8	54	70	81	43	72	74	83	21	77	20
Magnitude of dielectric dispersion	10	24	32	28	10	40	25	28	23	30	45
Cation exchange capacity	10	18	27	23	8	25	18	17	15	21	27
Expansion index	15	42	60	61	18	82	45	59	42	52	86

b. Equipment used : The following equipment and accessories were used to conduct experiments for the determination of the magnitude of dielectric dispersion.

i) Plexiglass cell — Basically, the cell consists of a simple cylindrical plexiglass tube with two platinum coated electrodes at the end of the tube. The cell is based on the principle of vectorial substraction of impedances measured at different electrode distances. This eliminates the influence of transmission line, electrodes themselves and the surrounding of the cell in general. The details of measurements, design of cell and its connections to the bridge terminal, and the calculations involved are described by Arulanandan and Smith (1973). The cell and the assembly are illustrated in Figs. 2 and 3.
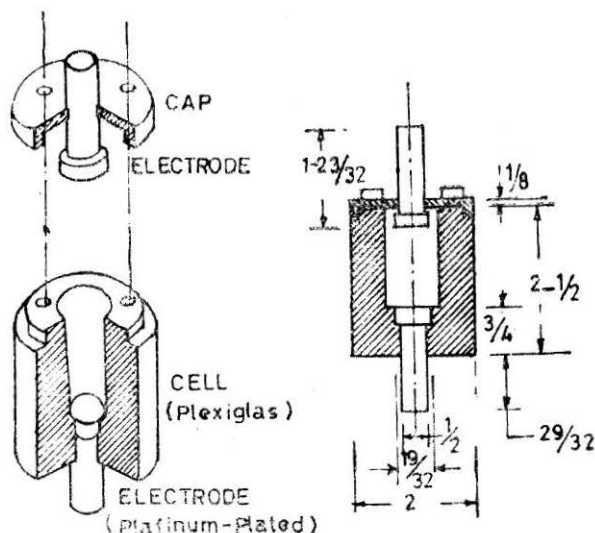

FIGURE 2   Cell for Radio-Frequency Measurements at Different Electrode Distances (dimensions are inches).

ii) Measuring device—The measuring instrument is an *RX* meter, which is basically a Schering Bridge with oscillator, amplifier detector, and null indicator designed to measure equivalent parallel conductance in the range of 0.0 to 0.067 mhos at frequencies between 0.5 and 250 MHz.

c. Experimental procedure : The soil is mixed with water to obtain a slurry at or about its liquid limit. This is packed into the cylindrical tube of the plexiglass cell and its resistance and capacitance are measured with *RX*-meter at different frequencies from 3 MHz to 75 MHz at about 25°C. These measurements are obtained at two different heights. Using equations 1 and 2, the dielectric constant and the conductivity are determined at different frequencies. More details about calculations are given by Arulanandan and Smith (1973).
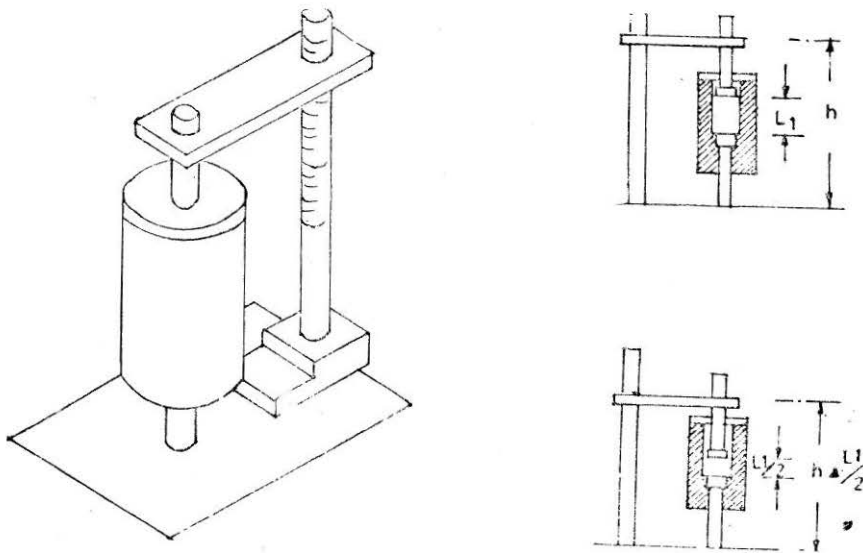
FIGURE 3 Schematic Representation of Cell and Transmission Line at Two Different Electrode Distances.

Results and Discussion

Cation Exchange Capacity

In engineering, electro-osmotic dewatering efficiency (Chapman, 1965) and erodibility predictions (Arulanandan, 1975) are made in terms of the cation exchange capacity (CEC) of soils. Therefore, a knowledge of the cation exchange capacity of soils and sediments is quite useful.

Fernando et. al. (1977) have reviewed the existing methods for determining the CEC. These methods are generally laborious and time consuming. The analytical procedures available for determining CEC often change two important factors affecting CEC, viz, the pH and the ionic strength of the fluid bathing of colloids. The determination is particularly poor if the sample contains amounts of colloids with pH-dependent change, that is, hydrons Mn and Al oxide, allophane or organic matter.

Fernando et. al. (1977) hence presented alternative approach to the rapid determination of CEC based on electrical properties of soils. Because the dielectric dispersion ($\triangle \epsilon$) is a variable parameter dependent on type of clay, clay content, valancy and size of exchangeable cations present, electrolyte concentration, structure, particle orientation etc., the overall contribution of these factors to the cation exchange capacity can be measured in terms of $\triangle \epsilon'$.

Fig. 4 show a linear correlation found between CEC and $\triangle \epsilon'$ for natural soils. It is seen that higher the CEC, higher is the value of the dielecric dispersion ($\triangle \epsilon'$). The significance of these results is that CEC can be predicted from a knowledge of $\triangle \epsilon'$ if a good correlation exists between these two parameters for natural (or artificial) soils available in a given region.
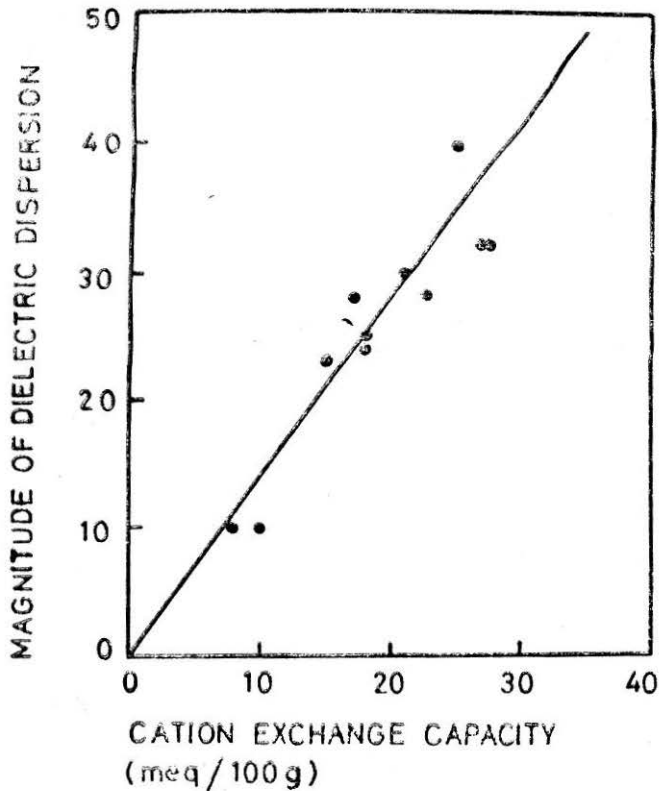
FIGURE 4 Magnitude of Dielectric Dispersion vs. Cation Exchange Capacity.

The determination of CEC requires a radio frequency bridge and the calculations involved are simple.

Expansion Index

The phenomenon of swelling and shrinkage associated with expansive soils is liable to cause considerable distress to structures founded on these soils. Therefore, the study of expansive soil in relation to problem of geotechnical engineering is of great practical importance and many research efforts are reported regarding the identification and behaviour of these soils.

The expansivity of soils is influenced by a number of factors such as soil structure, availability of water, electrolyte concentration in the water, stress history, time allowed for swell, initial degree and depth of desiccation in the soil, drainage conditions and temperature. Other important factors are initial density and moisture content, confining surcharge, and specimen size. Thus, it is clear that the expansivity is not a unique property of a soil and the identification and characterisation of potentially expansive soils is difficult and complex.

The methods currently available for the determination of expansion index of soil are tedious and time consuming. Since the magnitude of

dielectric dispersion ($\triangle \epsilon$') is a function of most of the factors affecting expansivity of soils, it could be used to measure the expansion index.

The magnitude of dielectric dispersion and the expansion index values were determined for the soils studied. The details regarding the determination of expansion index of soils are given by Krazynski (1973). The experimental results showed a linear relationship between the magnitude of dielectric dispersion ($\triangle \epsilon$') and the expansion index (Fig. 5). It is not surprising to obtain a high correlation between the expansion index and $\triangle \epsilon$' since both basically represent the water holding capacity of soil. The significance of the results presented in Fig. 5 is that it provides an alternative approach to the rapid determination of expansion index based on the electrical properties of soil.

Krazynski (1973) has suggested an identification criteria based on expansion index for expansive soils. Since a good correlation exists between the expansion index and $\triangle \epsilon$', an alternative criteria for the identification of expansive soils is suggested as shown in Table 3.

Identification of Dispersants and Flocculants

There is a large number of chemicals and industrial by-products available commercially as compaction aids. When fine-grained soils are treated with chemical compaction aids, two basic types of particle arrangements can occur : flocculated and dispersed. Due to the complex behaviour of clay-water-electrolyte systems, it is rather difficult to pin point a dispersion from a flocculant, and to study the degree of flocculation or dispersion by one single method when dealing with such chemical compaction aids. Since the magnitude of dielectric dispersion ($\triangle \epsilon$') is governed by the soil structure, any change in structure caused by flocculation or
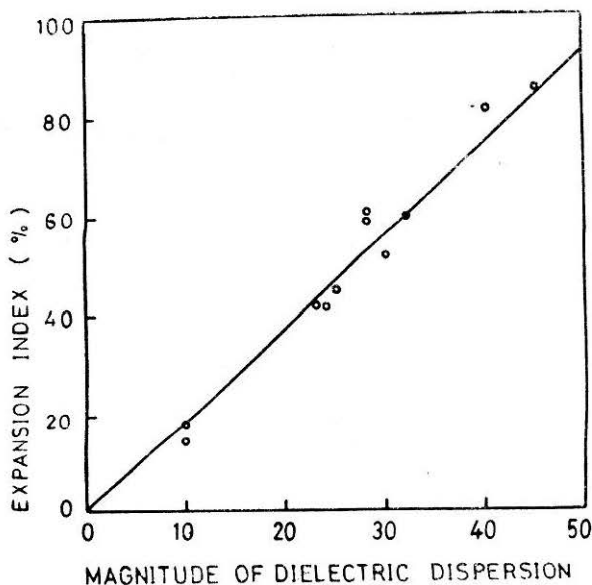

FIGURE 5   Magnitude of Dielectric Dispersion vs. Expansion Index.

TABLE 3 Identification Criteria for Expansive Soils

$\Delta\epsilon'$	Expansion Index (Per cent)	Degree of Expansion
<10	<20	Very low
11—25	21—50	Low
26—45	51—90	Medium
46—65	91—130	High
>65	>130	Very high

dispersion due to the addition of a chemical compaction aid will be reflected by a change in $\Delta\epsilon'$. Thus, the dielectric constant measurements in the radio frequency range can be used to identify dispersants and flocculants.

In a study conducted by one of the authors (Fernando, 1974) under the sponsorship of Federal Highways Administration (FHWA), U.S.A., eight commercially available compaction aids were studied with five different soils. The soils studied and referred to as in the U.S. included AASHO (52.5 percent passing 5 microns), LORING (27 per cent passing 5 microns), DECATUR (58 per cent passing 5 microns), SHELBY (40 per cent passing 5 microns) and LOESS (21 per cent passing 5 microns).

The soil passing 425-micron seive size was mixed with the chemical solution at or about its liquid limit. This was packed into the cylindrical tube of the cell and the dielectric constant measurements were obtained at different frequencies from 3 *MHz* to 75 *MHz* at about 25°C. $\Delta\epsilon'$ values were obtained as the difference of the dielectric constant at these extreme frequencies.

For standardization purposes, the results obtained for five soil types with eight chemical compaction aids are expressed in terms of Dispersion Index (D.I.) defined as

$$D.I. = \frac{\Delta\epsilon'_c - \Delta\epsilon'_w}{\Delta\epsilon'_w} \times 100 \qquad \qquad ...(3)$$

where $\Delta\epsilon'_c$ = magnitude of dielectric dispersion of soil with chemical solution

$\Delta\epsilon'_w$ = magnitude of dielectric dispersion of soil with water

The deduced values of D. I. are summarised in Table 4. A positive value of D.I. suggests a dispersed system while a negative value suggests that the system is flocculated. The magnitude of D.I. suggests the degree of dispersion or flocculation.

TABLE 4 Dispersion Index Values With Different Chemicals

Chemical	AASHO	Loring	Decatur	Shelby	Loess
SA—1	10.8	55.1	5.2	26.0	—14.3
SC—518	97.5	88.1	—3.0	96.3	55.4
Thin Water	47.5	—13.7	59.7	35.8	—21.8
Claset	79.2	—18.1	—51.5	—	13.2
SS—13	—12.5	12.3	68.8	62.2	—4.3
Road Packer	—20.0	1.8	—14.7	—9.3	—33.9
Packzyme	—22.5	—15.4	—14.3	63.0	—3.6
Pen-e-Pac	—	—15.0	—9.5	56.1	—1.32

Depending on the nature of the chemical added, the nature of the soil-water system could be completely changed to a dispersed or a flocculated state. Therefore, $(\triangle \epsilon_c' - \triangle \epsilon_w')$ is a measure of the net effect brought about by the solution of the chemical in water. Hence D.I. values based on $\triangle \epsilon'$ measurements of a soil in solution of chemical and in pure water can be used to characterise dispersants and flocculants.

If the positive values of *D.I.* are denoted by *D* and the negative values by *F*, Table 5 gives at a glance the nature of the chemical compaction aid with each soil. This table also suggests that any particular chemical does not behave as 'dispersant' for all soils.

TABLE 5 Soil Structure with Different Chemicals

Chemical	AASHO	Loring	Decatur	Shelby	Loess
SA—1	D	D	D	D	F
SC—518	D	D	F	D	D
Thin Water	D	F	D	D	F
SS—13	F	D	D	D	F
Claset	D	F	F	?	D
Road Packer	F	D	F	F	F
Packzyme	F	F	F	D	F
Pen-e-Pac	?	F	F	D	F

D = Dispersed state, *F* = Flocculated state.

The significance of this study is that the dielectric constant measurements can be used to characterise dispersants and flocculants.

Soil Classification

A number of soil classification systems have been proposed and used by engineers. Most of the earliest efforts to establish classification systems were based on the particle size limits of different soil components. The particle size definitions reported in various systems are summarised in Fig. 6. Although grain-size seems to provide a convenient means of classifying soils, it has major shortcomings. There exists many discrepancies among the various systems. Thus, a certain term may designate entirely different material depending on the system used. These systems based on particle size limits are purely arbitrary. There is little relationship between grain size and physical properties of fine grained soil. As a result, other soil classification systems, which incorporate consistency and plasticity characteristics of the fine fraction, have been developed and used. However, these systems do not provide knowledge on clay minerals, activity, swell potential, loss of shear strength with gain of moisture etc.

Review of current soil classification systems shows that they are mostly based on the compositional factors such as particle size distribution, mineralogical composition and colloidal properties, and they do not take into account the interaction of composition and environment.

The main aim of this discussion is to indicate that there is a need for a new classification system, based on the interaction of compositional properties and environmental factors, that will predict engineering behaviour of soils more accurately. It was indicated previously that the dielectric constant measurements of soils determine both the compositional and environmental influence. Thus, there is a good scope for research on the development of a new approach for classifying soils.

Fig. 7 illustrates the relationship between the magnitude of the dielectric dispersion and the type and per cent clay fraction in sand-clay
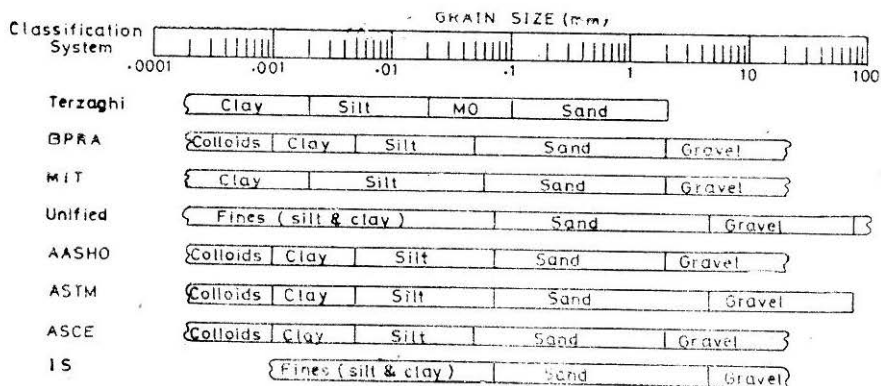

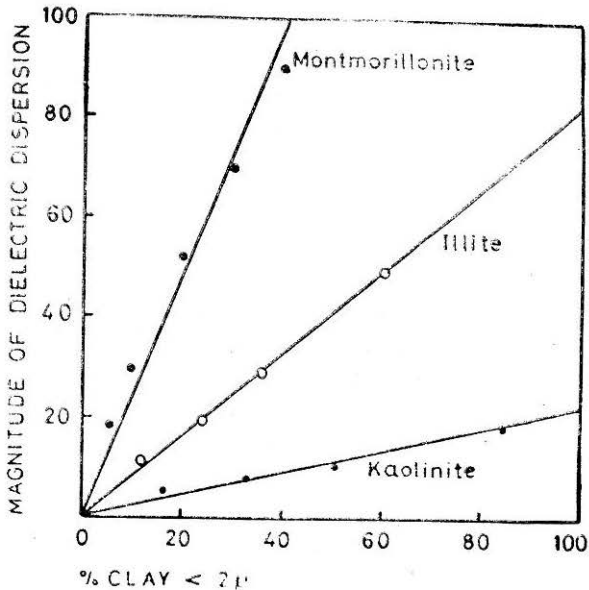Figure 6 Comparison of Classification Systems Based on Particle-size.

Figure 7   Relationship Between the Magnitude of Dielectric Dispersion and the Type and Proportion of Clay in Sand-clay Mixtures (artificial soils).

mixtures.   Since the behaviour of soil is a function of the type and proportion of clay in the soil (*e.g.* sand-clay mixtures), the linear variation of $\triangle\epsilon'$ with clay fraction obtained indicates that this property can be used to understand and predict several soil properties.   This forms the basis of a new approach for identification and classification of soils.

There is a good scope for research in this area and the interested researchers should carry out laboratory tests on various soil types with regard to their properties relating general stability, strength, drainage characteristics, volume change characteristics etc.   These results should be correlated with the corresponding dielectric constant measurements. Finally,   a suitable soil identification and classification system can be developed.

Soil Stabilisation

Recently, considerable attention is focussed to identify the origin of strength development in the stabilised soil.   Optical, differential thermal analysis,   electro-kinetics,   electron   microscopy   and   x-ray   diffraction techniques have been used in the past to study the composition and fabric in soil stabilisation.   Most of these methods are destructive, time consuming and expensive.

Some of the factors influencing lime-soil and cement-soil reactions include soil structure, mineralogy, water content, exchange capacity, pH, and percentage base saturation.   Since the electrical response of clay-water-electrolyte system in the radio frequency range is a function of these properties (Arulanandan and Smith, 1973), it should be possible to use dielectric constant and conductivity measurements to   monitor the reaction mechanism in lime and cement stabilisation continuously.

Castel (1972) attempted to use electrical responses of soils to predict the long term strengths from short term tests.

The main objective of this discussion is to show that the dielectric constant measurements have a great potential for research in the field of soil stabilisation. Some typical results are reviewed and discussed below :

Lime-Soil Stabilisation

Fig. 8 shows an attempt to correlate the 7-day unconfined compressive strength with the rate of conductivity. Each data point represents a different soil. It is observed that soils with higher decreasing rate of conductivity give higher 7-day strengths. If $\Delta\epsilon'^*$ represents the dielectric dispersion of lime-soil and $\Delta\epsilon'$ that of the untreated soil, then on plotting the change in dielectric dispersion ($\Delta\epsilon'^* - \Delta\epsilon'$) after one day against 7-day and 28-day strengths respectively, a linear relationship is obtained- Fig. 9 presents this relationship between the short term change in dielectric dispersion and long term gain in strength for different soil types. Thus, it is seen that the rate of conductivity and ($\Delta\epsilon'^* - \Delta\epsilon'$) can be used to predict the long term strength properties from the short term tests for lime-soil mixes.

Cement-Soil Stabilisation

Laboratory tests by Castel (1972) have shown that there is a clear increase in the magnitude of dielectric dispersion on addition of cement to soil. If $\Delta\epsilon'^*$ represents the dielectric dispersion of cement stabilised soil and $\Delta\epsilon'$ that of the untreated soil, it is seen from Fig. 10 that
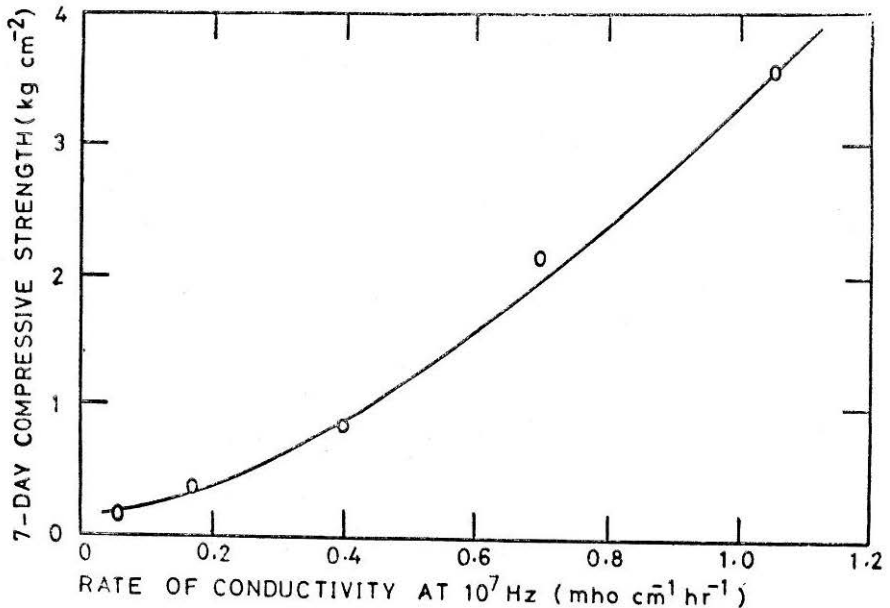

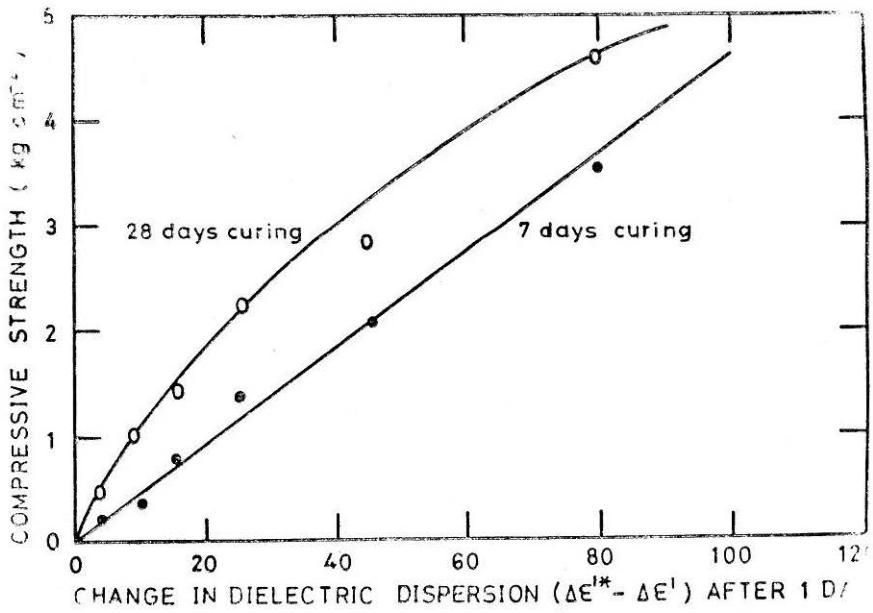Figure 8 Unconfined Compressive Strength (lime-stabilised soils) vs. Rate of Decrease of Conductivity.

Figure 9   Unconfined Compressive Strength (lime-stabilised soils) vs. Change in Dielectric Dispersion.
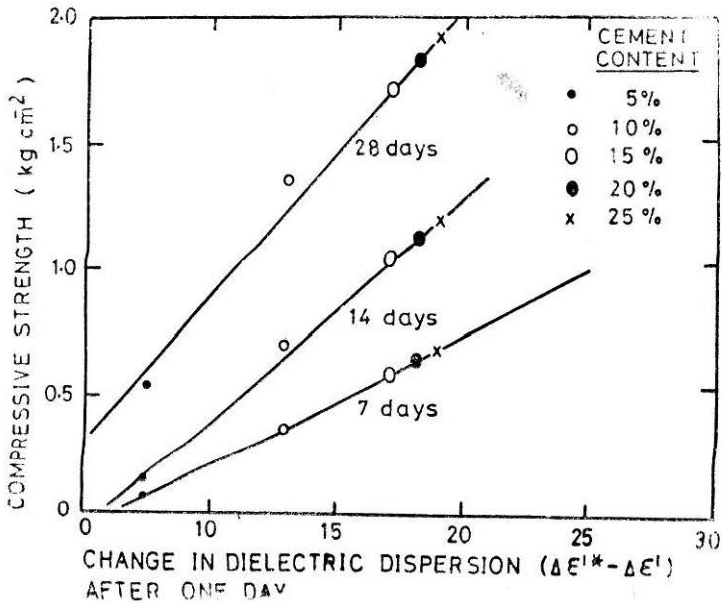

Figure 10   Unconfined Compressive Strength (cement-stabilised soils) vs. Change in Dieletric Dispersion.

($\triangle\epsilon'^* - \triangle\epsilon'$) in one day is linearly related to unconfined compressive strengths at different curing times for various cement contents and soil types.

It was observed that the conductivity of cement-soil mixes decreased with curing time. A typical plot representing different soils is shown in Fig. 11. The rate of decrease in conductivity with time for different soils stabilised with cement is found to be different.

It is pointed out that the conductivity measurements are significantly affected by the type (valancy and size) of exchangeble cations already present. The conductivity measurements would therefore automatically include the contribution of the exchangeable cations present. Hence, the conductivity measurements provide a potential means for the prediction of long term strength properties of stabilised materials.

The significance of the above study is that the conductivity and ($\triangle\epsilon'^* - \triangle\epsilon'$) measurements after one day are good predictors of long term strengths for cement-stabilised soils.
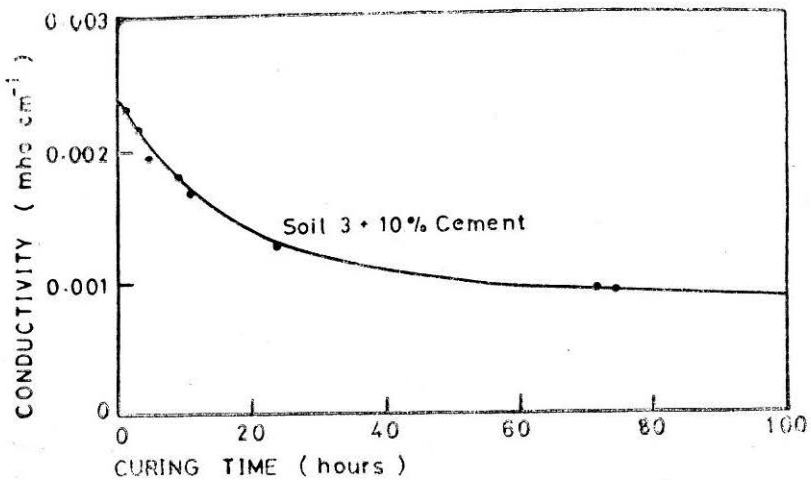

Figure 11   Variation of Conductivity with Curing Time.

Conclusion

The soil behaviour is governed by a complex interaction of compositional properties and environmental factors. It is evident from this paper that the dielectric dispersion incorporates and determines this interaction. Thus, the dielectric dispersion is a basic soil parameter that provides a potential tool for geotechnical investigations.

The dielectric dispersion measurements have been applied to some areas of geotechnical engineering. It is found that the cation exchange capacity and the expansion index of clay soils can be predicted from a knowledge of the dielectric dispersion. The relationships required for this are presented. An alternative criterion for identification of expansive clays is proposed.

The dielectric dispersion of a soil is shown to be useful for characterising dispersants and flocculants.

For a more accurate characterisation of soils and prediction of their engineering behaviour, any soil classification system should be based on the interaction of compositional properties and environmental factors. There is a good scope for research utilising the proposed approach to evolve a suitable identification and classification system for soils.

The dielectric dispersion is a useful means to study the overall reaction mechanism in stabilised soils. It is possible to predict the long term gain in strength of lime and cement stabilised soils using the dielectric dispersion measurements after one day curing. There is good scope for further research.

The chief advantage of the proposed approach for geotechnical investigations is that it is fundamental in nature, involving simple and easy to perform laboratory tests.

Acknowledgement

References

ARULANADAN, K., (1975) "Fundamental Aspects of Surface Erosion of Cohesive Soils", Journal of Hydrol. Division, ASCE, Vol. 101.

ARULANANDAN, K., BASU, R., and SCHARLIN, R., (1973) "Significance of Magnitude of Dielectric Dispersion in Soil Technology", Highway Research Board Record 426.

ARULANANDAN, K. and SMITH, S.S., (1973) "Electrical Dispersion in Relation to Soil Structure", JSMFD, ASCE, 99 : SM 12.

CASTEL, A., (1972) "*Lime and Cement Stabilitisation*", M. Sc. Thesis, Univ. of California, Davis, U.S.A.

CHAPMAN, (1965) "Cation Exchange Capacity", in "Methods of Soil Analysis", C.A. BLACK (ed-in-chief), Part 2, Agronomy 9, Am. Soc. of Agron., Madison, Wis., U.S.A.

CHAUHAN, S.P.S., (1982) "Effects of Certain Factors on Electrical Resistivity of Soil — An Experimental Study", M. Tech. Thesis, Indian Institute of Technology, New Delhi.

CHAUHAN, S.P.S., and KATE, J.M., (1983) "Experimental Studies on the Effects of Density and Moisture Content on Resistivity of Soils", Indian Geotechnical Journal, 13 : 1.

FERNANDO, M. J., (1974) "Measurement of Dielectric Constant of Soil-Water Systems with Chemical Compaction Aids", Report submitted to Civil Eng. Dept., Iowa State Univ Report No. FHWA-DE-19-63, Vol. 1.

FERNANDO, M.J., BURAU, R.G., and ARULANADAN, K., (1977) "A New Approach to Determination of Cation Exchange Capacity", Journal of Soil Science Society of America, 41 : 4.

KATE, J.M., (1979) "Electrical Resistivity of Certain Soils", IGS Conference on Geotechinical Engineering, New Delhi.

KRAZYNSKI, L.M., (1973) "Proc. of Workshop on Expansive Clays and Shales in Highway Design and Construction", Vol. 1, Federal Highways Administration (FHWA), U.S.A.

MALHOTRA. B.R., (1979) "Electrical Resistivity Method as Applied to Geotechnical Investigations". Indian Highways, Indian Roads Congress. New Delhi, 7 : 2.

MITCHELL, J.K. and ARULANANDAN, K., (1968) "Electrical Dispersion in Relation to Soil Structure", Journal of Soil structure, *JSMFD*. ASCE, 58 : SM 2.