# Frequency Dependent Permittivity of Soil and Bentonite: For Lightning Protection and High Frequency Earthing Systems

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***Abstract*— This paper presents the frequency dependent permittivity of a selected type of soil, bentonite and four of their mixes by weight. The permittivity at a low frequencies, vary significantly with moisture content in the cases of both sand and bentonite. For dry sand, bentonite and all bentonite mixes, the permittivity shows a rapid drop with the increment of frequency from near 0 Hz to 0.6 kHz, followed by a moderate decrement up to about 10-20 kHz. All parameters have rather insignificant variation after about 50 kHz and level of around 1MHz. These outcomes provide some key information to analyze the behavior of bentonite based backfill materials that are widely used in electrical earthing networks, especially in the case of high frequency earthing and lightning protection systems.**

***Keywords*— *lightning, earthing, high frequency, bentonite, permittivity, electrical parameters***

## I. INTRODUCTION

In the recent years, bentonite based backfill materials became very popular among the earthing system contractors and design engineers, specifically in the earthing of electrical systems in high resistive soil [xxx]. Bentonite is a natural clay found in many parts of the world. It is a complex combination of montmorillonite and hygroscopic clay of which the chemical structure is given by $(Na,Ca)_{0.33} (Al,Mg)_2 (Si_4O_{10}) (OH)_2 \cdot n(H_2O)$. It has a molecular structure, which is an octahedral sheet of aluminum atoms, sandwiched between two tetrahedral layers of silicon atoms. Macroscopically, the composition of predominantly behave as a smectite where its physical and chemical nature has a smectite dominance

There are several studies done on the electrical properties of bentonite and their mixes under DC or low frequency conditions [1-5], however, there are almost no work done on the variation of these properties with varying frequency. This is a significant drawback in studying the behviour of earthing systems embedded in such materials under high frequency or lightning current injections. This is evident as there are several studies done on the breakdown characteristics of bentonite and other similar materials, where the published literature reports only the observations without attempting to interpret the results or develop mathematical/simulation models [3-5]. Several theoretical studies, simulation works and experimental investigations have been done on soil and hypothetical earthing materials to find their frequency response; however, bentonite has not been a subject of investigations in determining its electrical parameters [6-9].

Electrical earthing is done under various outdoor conditions that experience a range of weather patterns, thus the moisture levels of materials used as backfill materials may change with time. The effects of such changes in soil or bentonite have not been comprehensively analyzed yet. In this backdrop, an experiment has been conducted to analyze the electrical properties of soil and bentonite for frequencies in the range of 0 Hz – 100 kHz. The experiment considered bentonite, soil, and mixtures of soil and bentonite with varying composition ratios. Further, the effects of moisture in bentonite, soil and mixtures on electrical parameters were also investigated. This paper reports only the variation of permittivity of the materials considered. The outcomes of the investigations done on the frequency dependent permittivity are reported in Reyad et al [10].

## II. METHODOLOGY

The test samples used in this study include soil and bentonite as it is summarized in Table 1. The physical and chemical properties of bentonite used in this experiment is given in Lim et al [1]. The bentonite used for this experiment are from the same stocks used for the investigations reported in [1] and [3].

Sieve analysis, has been used to classify the particle size distribution of the materials that has been used [11]. Several sieves with varying filter-mesh sizes were used to find the percentage of the distribution of course, large-sized and small-sized particles. Size distribution of finer particles were determined by hydrometer method [11]. The USDA recommended soil texture triangle [12] was employed in determining the textural class of particles. The objective of this test is to assign a recognized type to the selected soil.

The permittivity was measured by a hollow Perspex box of inner space dimensions 10 cm × 10 cm × 10cm. Two aluminum plates were fixed to inner opposite walls and the test material (soil, bentonite, mixes etc.) was added in to the hollow space between the plates (refer [10] for details).

Sample preparation of dry materials was done by heating the soil in an oven until the weight of the soil became constant within a precision of ±10 µg. The dry samples were added measured among of water by a sprinkler bottle and mixed with an electrical mixer for about 10 mins. In the event of excess water (more than required for a given weight percentage of moisture) it was heated in the oven again with regular weight measurement. For each material, samples were prepared with moisture levels ranging from almost zero percent (considered as dry) and 10%, 20%, 30%, 40%, 50% and 60% by dry material weight. Measurement of electrical parameters were done immediately after the sample attain the required moisture level.

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Measurements on electrical parameters were done by a frequency variable LCR meter (Instek-LCR-8110G High Precision) and a digital storage oscilloscope. Each sample was tested for a frequency range of 0 Hz (steady state) - 3 MHz. The readings were repeated for three samples having the same composition to get a statistically significant set of data. The permittivity of the material across the frequency spectrum was recorded stepwise (at 400 non-uniformly distributed frequency points) for each samples. The values of the three samples at each frequency point has been averaged. Although, we continued the measurements up to 3 MHz, in this study, we present the data in detail only up to 50 kHz as the permittivity of all samples level off significantly within this frequency limit. However, we discuss the observations up to 1 MHz.

Table I Material combinations

| Material | Sand-Bentonite ratio in percentages |
|---|---|
| Sand | 100% - 0% |
| Mix-1 | 75% - 25% |
| Mix-2 | 67% - 33% |
| Mix-3 | 50% - 50% |
| Mix-4 | 25% - 75% |
| Bentonite | 0% - 100% |

## III. RESULTS AND DISCUSSION

The particle size distribution of the sand sample is found to be as follows. Particles with size;

greater than 500 mm: 49%

between 20 and 50 mm: 27%

between 250 - 500 mm: 10%.

With these percentages, as per the USDA soil texture triangle [12], this soil is categorized as having 64% sand, 31% silt and 2% clay. Thus, it falls into the zone of sandy loam (Figure 1).

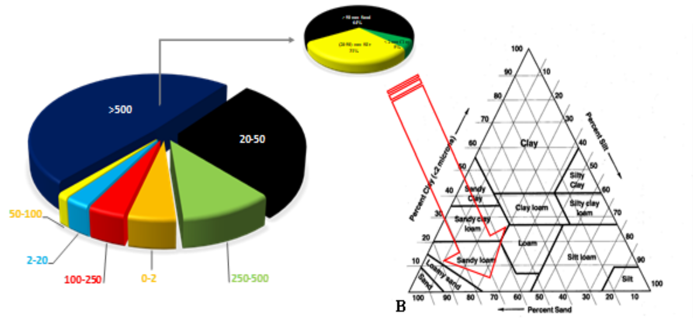

Figure 1. Particle size distribution (microns) of Sand

Figure 2 depicts changes of permittivity of sand samples with frequency. As it was expected, the permittivity reduces with frequency. The dry sand (sandy loam) has a relative permittivity of approximately 100 at near zero Hertz. For all moisture levels other than the dry condition (zero moisture), the permittivity decrease in a similar variation which resembles inverse or inverse square relation with frequency. In this paper we do not made attempts to develop an empirical model (curve fitting) to describe this behavior. The variation of the permittivity of dry sand will be discussed latter. The permittivity at near zero frequency of soil samples has values that range from 10 times to 18 times of the permittivity of dry sand as the moisture level increases from 20% to 60%. This fact should seriously be taken into account in the designing of earthing systems in arid and semi-arid areas where the sand is extremely dry. The difference in permittivity among the soil samples with increasing moisture level diminishes as the frequency increases and becomes insignificant after about 20 kHz. This may be of importance in computing the impedance of lightning protection and HF earthing systems. In comparison with the difference in the permittivity between the soil samples with different moisture levels at low frequencies, the same differences become insignificant around 50 kHz. As the frequency reaches about 1 MHz all curves merge with one another.

It is a well-known fact that the soil parameters are quite sensitive to the frequency [8, 9]. As per the variation of permittivity with frequency given in the literature [7, 13-14] one can clearly see that the permittivity rapidly drops with frequency up to about 10 - 20 kHz and then the rate of decrease becomes slower. Note that the frequency of the curve is given in a logarithmic scale in most of these papers. Almost all work in the previous literature defines soil types by their low frequency resistance. Thus we cannot relate our results directly to the outcomes of the previous work. However, in general, the variation patterns of permittivity of the soil with frequency are in well agreement with the previously observed behaviors of soil.

Figure 3 depicts changes of permittivity of bentonite with frequency. In all cases of moisture levels, bentonite samples showed a similar variation in permittivity at low frequencies. The permittivity drops drastically from the near zero-frequency value up to about 600 Hz before the curves flattening out. From 600 Hz up to about 1 kHz, the variation of the permittivity shows some slight discontinuity before following a smooth slow drop in value. In the case of soil, this behavior could be observed only in the case of dry sample (Figure 2 and Figure 4). We do not make attempts to interpret this observation in terms of physics or morphology of the material. However, the observation of this behavior alone will have a significant importance in the modelling of breakdown characteristics of the material under impulse and HF voltages. The permittivity of bentonite also shows a behavior similar to that of the soil, at higher frequencies. The difference of the permittivity values becomes comparatively insignificant at about 50 kHz and the curves almost merge around 1 MHz.

Interestingly the increase of permittivity of bentonite at near-zero frequencies does not show a sequential increase in the value of permittivity with the percentage of moisture as it is observed in the case of soil (figure 3). Similar behavior is observed in the case of the variation of bentonite content at all levels of moisture content. We only provide the cases of dry material (Figure 4) and 10% moisture (Figure 5) in this regard to illustrate the observation.

The outcomes clearly depicts that models that consider the permittivity is constant with frequency (for all frequencies or up to a certain upper frequency limit, such as that is proposed by Visacro and Alipio [14] may introduce significant errors in computing earth potential rises, soil breakdown characteristics etc., under lightning and high frequency conditions. [7]. The permittivity of bentonite and its mixes with soil shows much complex patterns of behavior with frequency as the moisture content, mixing ratios vary. These observations infer that the breakdown characteristics and earth potential rise in the case of earthing systems embedded in such backfill materials need further attention with respect to these variables in the simulation models.

This paper presents only the variation of permittivity of soil and bentonite (and their mixes) with frequency as a function of moisture content. Reyad et al [10] which provides the variation of resistivity with frequency for the same materials could be incorporated with the information that is provided in this paper to have a complete simulation model for such materials.

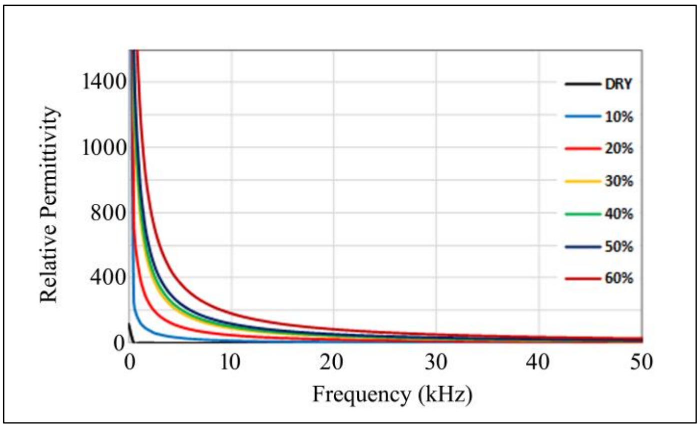


Figure 2: Permittivity for soil as a function of frequency and moisture content.

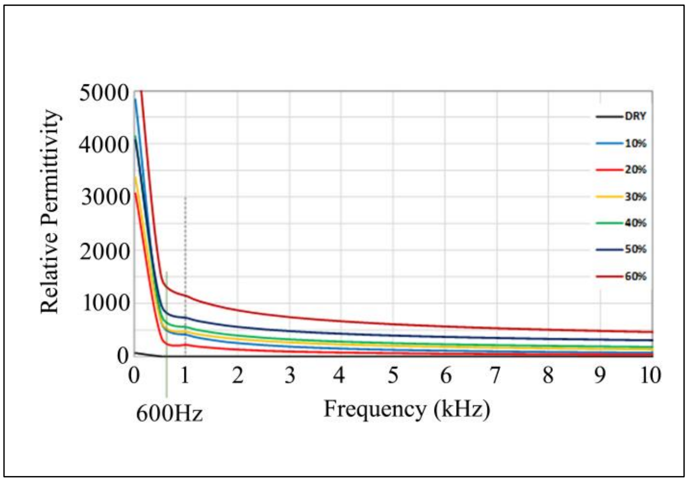


Figure 3: Permittivity of bentonite as a function of frequency & moisture content

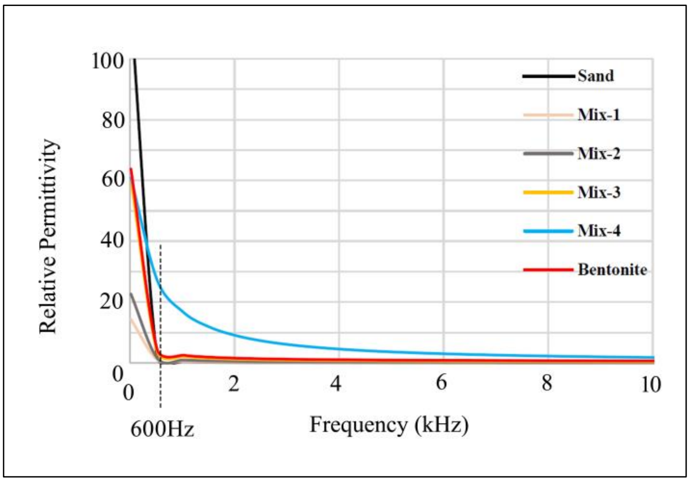


Figure 4: Permittivity of dry sand, bentonite and mixes as a function of frequency (0% moisture content).

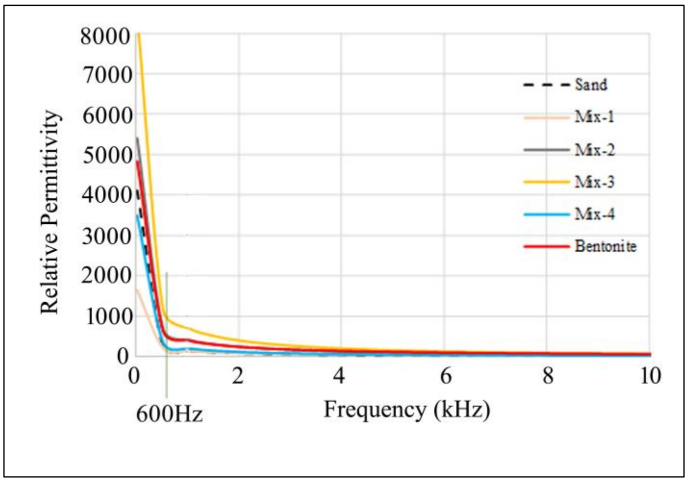


Figure 5: Permittivity for sand, bentonite and mixes as a function of frequency (10% moisture content)

## IV. CONCLUSSIONS

Results obtained from the experiment identify patterns of permittivity variation with frequency of soil and a common backfill material bentonite. The significant variation of permittivity of all materials with frequency up to about 20 kHz, suggest that there could be some serious flaws of the calculation of earth potential rise, breakdown characteristics etc. of such materials by considering constant electrical parameters in this frequency range. Therefore, the use of DC characteristics of backfill materials and soil in grounding system development is not advised as switching surges and lightning are a common occurrence and both these phenomena consist of multiple frequencies. In other words, the performance of the grounding system can be compromised if the frequency dependency characteristics of resistivity and permittivity are not taken in to account.

In the case of dry soil, bentonite and soil-bentonite mixes, there is a drastic reduction of permittivity from near-zero Hertz to about 600 Hz. This is a new information which should be explained in fundamental principles in future studies. The difference in the permittivity of a given material with different moisture levels diminishes with increasing frequency and becomes rather insignificant around 50 kHz. The curves almost merge above 1 MHz. Thus as the frequency of grounded or surface currents reaches HF spectrum the moisture level in the soil or backfill material becomes negligible with respect to the variation of permittivity. .

In the present era, bentonite is a common backfill material in electrical earthing systems, which is mixed with soil to reduce ground resistivity. It is of importance to identify ground resistance after the backfill material is added. Data collected through this experiment provides evidence that the ground resistance is not a constant even at DC conditions when a backfill material is added. The concentration of the backfill material with the soil and the moisture level is a key factor in achieving the required resistivity.

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## REFERENCES

[1] S. C. Lim, C. Gomes, and M.Z.A. Ab Kadir, Characterizing of bentonite with chemical, physical and electrical perspectives for improvement of electrical grounding systems. International Journal of Electrochemical Science, 8(9), 11429–11447, 2013.

[2] S. C. Lim, C. Gomes, and M.Z.A. Ab Kadir, Electrical earthing in troubled environment. International Journal of Electrical Power and Energy Systems, 47(1), 117–128, 2013.

[3] S. C. Lim, C. Gomes, and M.Z.A. Ab Kadir, G. Nourirad, and Z. Abdul-Malek, Behaviour of backfill materials for electrical grounding systems under high voltage conditions. Journal of Engineering Science and Technology, 10(6), 811–826, 2015.

[4] H. Rusli, C. Gomes, M.Z.A. Ab Kadir, and Z. Abdul-Malek, Surface arcing of insulators due to bentonite contamination. Journal of Electrostatics, 76, 73–77, 2015.

[5] R. Z. Sabry, C. Gomes, M. Izadi, M.Z.A. Ab Kadir, H. Hizam, and J. Jasni, Experimental investigation on breakdown characteristics of sand, bentonite and their mixes. Journal of Electrostatics, 93, 79–84, 2018.

[6] H. Hasan, H. Hamzehbahmani, H. Griffiths, D. Guo and A. Haddad, Characterization of Site Soils using Variable Frequency and Impulse Voltages, 10th Asia-Pacific International Conference on Lightning (APL2017), Krabi, Thailand, 1-4, 2017.

[7] S. Visacro, R. Alipio, M. Helena, M. Vale, and C. Pereira, The Response of Grounding Electrodes to Lightning Currents: The Effect of Frequency-Dependent Soil Resistivity and Permittivity, 53(2) 401–406, 2011.

[8] C. M. Portela, Frequency and transient behavior of grounding systems I - Physical and methodological aspects, IEEE 1997, EMC, Austin Style. IEEE Int. Symp. Electromagn. Compat. Symp. Rec. (Cat. No.97CH36113), 379–384, 1997.

[9] C. M. Portela, J. B. Gertrudes, M. C. Tavares, and J. P. Filho, Influence of earth conductivity and permittivity frequency dependence in electromagnetic transient phenomena - more measurements results in new sites, IEEE/PES Transm. Distrib. Conf. Expo. Lat. Am. (IEEE Cat. No. 04EX956), 2004.

[10] R. Z. Sabry, A. Gomes, C. Gomes, M.Z.A. Ab Kadir and N. B. Misron, Frequency dependence of the resistivity of soil and bentonite: With special attention to electrical grounding systems, Engineering Reports, 2019 (under review).

[11] A. J. Ujam and K. O. Enebe, Experimental analysis of particle size distribution using electromagnetic sieve. American Journal of Engineering Research (AJER), 02(10), 77–85, 2013.

[12] D. G. Groenendyk, T. P. A. Ferré, K. R. Thorp and A. K. Rice, Hydrologic-process-based soil texture classifications for improved visualization of landscape function. PLoS ONE, 10(6), 1–11, 2015.

[13] R. S. Alipio, M. O. Schroeder, M. M. Afonso, T. S. Oliveira, and S. C. Assis, Electric fields of grounding electrodes with frequency dependent soil parameters, Electr. Power Syst. Res., 83(1), 220–226, 2012.

[14] R. S. Alipio and S. Visacro, Frequency dependence of soil parameters: Effect on the lightning response of grounding electrodes, IEEE Trans. Electromagn. Compat., 55(1), 132–139, 2013.