Review of constitutive parameters of building materials

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I. INTRODUCTION

With continuing advances in the computing power of computer systems and the increasing availability of building and terrain data, deterministic propagation modelling approaches are becoming increasingly realistic for practical implementation. The accuracy of these methods depends on both the positional accuracy of the building and terrain involved, and on the accuracy of the constitutive parameters of the media involved. This is true especially in environments where radio wave propagation is mainly due to propagation mechanisms without a strong line of sight contribution.

The purpose of this paper is to provide a comprehensive review of the constitutive parameters of common building materials, reporting on the important composition characteristics and frequency dependent behaviour of these materials.

The importance of this review comes from the need to specify the constitutive parameters in a sensible way. A clear understanding of the involved processes can allow the propagation modeller to make reasonably accurate assumptions on the variation and validity of the constitutive parameters, for frequencies or frequency ranges that have not been reported in the literature. This paper includes some references, which are difficult to find since they do not appear in the literature usually accessed by the propagation modelling community.

II. MEASUREMENT TECHNIQUES

Since this review is concerned with the constitutive parameters of building materials, this section introduces some of the measurement techniques used to measure these parameters.

Some of the most common methods used to measure the dielectric properties of different samples are the following: microwave free space, two terminal measurements, time domain spectrometry, frequency domain, open resonator, closed cavity, dielectric probe, waveguide techniques [1][2].

From the above, the most frequently used technique for measuring the transmission and reflection coefficients under an angle of incidence, at microwave frequencies, is through the microwave free space method and the use of a turntable. This setup usually takes place in an anechoic chamber. This environment allows the absorption of unwanted reflections that can alter the received field. This method often uses a wideband technique to distinguish the path penetrating through the material from other contributions. Directional antennas with small beam widths are also used in order to avoid or further reduce any diffraction effects around the edges of the material under investigation.

III. BUILDING MATERIALS

In order to evaluate the reflection and transmission coefficients, which quantitate the RF reflection and transmission loss, the constitutive parameters of the material of interest should be known. Since it is practically impossible to know the exact value of these parameters for all environments, one should be able to make sensible predictions. For this reason it is important to review a number of measurements carried out at different frequencies and for different materials. Although the literature presents a number of measurements for different materials, this paper concentrates on those frequencies, which will be of most use. At the same time the highlighted references can assist the propagation modeler to draw conclusions for other frequencies.

For the purpose of this review the building materials are classified in 3 categories. First category includes bricks concrete etc, materials which are usually used for hardened walls. Second category refers to glass since glass usually provides a relatively low loss propagation path and third category refers to wood and wood based materials.

Parameters presented and discussed here will cover mainly the VHF, UHF and lower microwave range. For lower or higher frequencies one should further consult the references.

A. Bricks, Concrete and Limestone

Brick measurements carried out in the 1.7-18GHz range [3][4], have highlighted an electrical permittivity range between 4.62 (1.7GHz) and 4.11 (18GHz), with in between values that do not necessarily decrease linearly. For the same frequency range, conductivity (S/m) was found to vary between 0.0174 and 0.0364. In another set of measurements [5] [6], which refer to 3 different brick types (Gault, Hamill, Leicester red and Fletton brick) at 3, 9 and 24 GHz, the electrical permittivity was found to have almost a constant value of around 3.7-4 for 0% water volume at all frequencies. From the plotted data it is obvious that for 0 or small volumes of absorbed water, the real and imaginary parts of the complex permittivity at 3 and 9GHz are almost the same for all brick types. For the 24GHz case although this is true for the real part of the complex permittivity, the imaginary part appears to be lossier for the same set of conditions compared with the 3 and 9GHz case. The imaginary part of the complex permittivity was found to vary between 0.12 (3 and 9 GHz) to 0.6 (24GHz) for 0 water volume. It is worth mentioning that, for frequencies between 3 and 24 GHz, in the case where the water volume changes from 0 to 30%, the real part of the complex permittivity can vary from 3.7 to 19 and the imaginary part from 0.12 to 3.7. Theoretical ways are also presented for calculating the real and imaginary parts of the complex permittivity of brick, yielding results that in many cases are in close agreement with the practical measured values [5][6][7].

Concrete is made by adding water to a mixture of cement, sand (fine aggregate) and coarse aggregate. Hydration takes place between the water and cement producing a matrix of compounds known as cement paste. This matrix locks together the coarse and fine aggregate particles to form a material with considerable compressive strength. A concrete mix is normally defined by the mass ratios of its constituents, i.e.: the water/cement ratio, the cement/sand/aggregate ratio and the cement/total-aggregate ratio

In the concrete case the real and imaginary parts of the complex permittivity of different concrete mixes have been investigated by a number of authors [5][6].

Data presented by the above authors refers mostly to the real and imaginary parts of the complex permittivity of hardened concrete. This data characterises the complex permittivity for different water-cement ratios, for conditions of different water volume absorption. Results were recorded at 3, 9 and 24GHz. For the case of interest where concrete can considered dry or having a small water content, the real part of the complex permittivity was found to vary between 5-7 while the imaginary part between 0.1-0.7.

Data was also recorded for aerated concrete at 3 and 9GHz [5]. Aerated concrete consists of a cement paste to which a small proportion of aluminium powder is added. During the heating process the aluminium is oxidized producing sufficient hydrogen to aerate the mix into a strong lightweight material. In this case and for small water contents, the real part of the complex permittivity was found to vary between 2-2.5, while the imaginary part between 0.12-0.5.

All the constitutive parameters presented up to now for different concrete types, do not vary significantly from data recorded by other sources [10]. In the latter case for the range of frequencies 1-95.9GHz the real part of the complex permittivity was found to vary from 6.2-7 and the imaginary part from 0.34 to 0.85 for hardened concrete. In the same reference, aerated concrete measured at 1GHz was found to have a value of $\varepsilon_{complex}$=2-j0.5 which is close to the values reported at 3 and 9GHz in [5]. Similar measurements between 0.5-0.7GHz suggest a value for the relative permittivity between 2.5-3 and a conductivity range between 0.0138-0.025.

The data presented up to now, suggests that the complex permittivity of concrete samples does not vary significantly due to frequency changes, even over a wide frequency range. It also does not change significantly for different mixing ratios of similar materials. It seems that the biggest difference observed is between hardened and lightweight, aerated, concrete samples.

The concrete parameters presented above referred to non reinforced concrete samples. In the case of reinforced concrete, it has been shown that other parameters that can influence the transmission characteristics of a concrete wall include the square grid side length and the steel diameter used in the reinforced concrete. Even in these cases, the value of complex permittivity used to describe the concrete was equal to $\varepsilon_{complex}$=7-j0.3 for 900 and 1800MHz [9].

B. Glass

The chemical structure of glass is constituted from a network of oxygen polyhedral in the centre of which, network-forming ions as Si^{4+}, B^{3+}, and P^{5+} exist. Some of these polyhedral have common corners, forming other oxygen polyhedral networks with large open spaces. Depending on the chemical composition of the specific glass, these open spaces can be taken up by different network-modifying ions like Li^{+}, Na^{+}, K^{+}, Pb^{+}, Ba^{++}, Ca^{++}, Mg^{++} etc.

Glass usually occupies a significant area of the external wall of buildings and in most cases will provide a relatively low loss path to electromagnetic waves. This makes the investigation of glass equal important to brick and cement and in many cases even more. Describing glass with the correct constitutive parameters is crucial, when estimating the contributed field through a low loss windowed area, since it can influence the accuracy of the prediction.

The electrical permittivity of glass has been found to vary strongly with glass composition but not with frequency. For fused silica glass it has been found to be around 4. For commercial glasses, electrical permittivity usually lies between 4 and 9 covering the lower VHF to microwave range [11][12][13][14][15]. In order to obtain higher values of permittivity, network modifiers should be used, like the ones mentioned in the previous paragraph. In general PbO and BaO are components, which impart high values of permittivity to glass structures. Under these conditions special glasses can be constructed having a permittivity of the order of 20. Furthermore it has been found that permittivity changes with increasing temperature and this is based on the fact that at higher temperatures the ions are more mobile.

In [11] the general shape of $\tan\delta$ as a function of frequency is shown, where the minimum and maximum magnitude positions would differ for different glass compositions. This general behavior is in agreement with a substantial amount of measurements recorded for different types of glasses and frequencies [11][12][13][14][15]. A typical range of values for loss tangent in the VHF to microwave range lies between 0.00005 and 0.0350.

The value for loss tangent can be obtained as the sum of four different contributions:

The conduction losses, which are due to the influence of an electric field force on the network modifying ions. It is also important to note the relation between the conduction losses and the relative humidity, where it has been shown that conduction losses become significant at 50% relative humidity. This is because a coherent monolayer of water is not formed until the relative humidity is as high as 50%.

Dipole relaxation losses. These losses are produced through the ability of mobile ions to jump over small distances in the network under the influence of an electric force so that a number of lower potential barriers can be covered.

Deformation losses. These losses are produced again due to the ion movements under the influence of an electric field but in this case these movements are much more restricted than in the two previous cases hence the name deformation.

Vibration losses. These losses are produced when an electric field is applied with a frequency approximately equal to the vibration frequency of an ion and resonance might occur. Since ion vibrations are always damped the resonance is accompanied by losses.

The loss tangent will vary, depending on the chemical composition of the glass under investigation, with respect to the above phenomena. For example in the series of alkali ions, mobility for these ions decreases from lithium to caesium. The conduction and dipole relaxation losses are therefore expected to decrease in the same way since these losses are related to the ion movement [11].

C. Wood

When an electromagnetic field is applied to wood or wood based materials, the electrical properties are defined by different polarisation processes as a result of the interactions between the molecules of the wood material and the external field. The polarisation effect is caused by the space change arrangement of the wood’s electrically charged particles, under the influence of this external field similar to the glass case. The total polarisation effect on wood is constituted by the following five types: The electronic polarisation P_e,, The Ionic (atomic) polarisation P_a,, the Dipole polarisation P_d, the Interfacial (structural) polarisation P_v and the Electrolytic polarisation P_z.

Depending on the operating conditions like the frequency of the applied electromagnetic field, the effect of the different polarisations on the overall polarisation process would be different and as a result the dielectric properties of wood will vary. Furthermore, depending on the frequency range, some kinds of polarisation are not taken into consideration because of the very short time constants involved. This time constant is the time taken to produce a specific polarisation. In the range of 100 kHz to 10GHz only dipole and interfacial kinds of polarisation are important [16].

Like other building materials, the relative permittivity and loss tangent of wood depends on a range of different factors. These factors include the type of wood involved (tree species), the wood density, water content [17], the temperature, frequency of operation and any special chemical treatment to which the wood has been subjected. The latter is done in order to impart to wood special properties like biological resistance to water absorption [18]. The water content is been expressed as the dimensionless ratio of the mass of water present in the sample, to the mass of the sample after it has been dried to a constant weight. It has been found that as moisture or water content increases, electric conductivity increases and the behaviour of saturated wood approaches that of water. Another important factor that has been found to influence the dielectric parameters of wood is the electric field orientation in relation to the direction of grain.

Literature [16] suggests an extensive range of empirically measured constitutive parameters covering the frequency range of 20Hz to 100GHz, for different moisture contents and wood densities. In this frequency range for the oven dry wood case and a density ρ_0(g/cm^3) 0.13-1.53, the relative permittivity was found to vary from 1.2 to 6.8 and the loss tangent from 0.005 to 0.063. These results refer to the case where the electric field is applied across the grain at a temperature of 20-25^{o}C. For the same set of conditions and in the frequency range of 100MHz to 10GHz where most common systems will operate, these parameters vary respectively between 1.2-4.5 and 0.007-0.061. It is important to note that in cases where wood cannot be considered dry but instead has a moisture content of 0-100%, for wood densities between 0.3-0.8 ρ_0(g/cm^3), a frequency range of 10KHz-10GHz and a temperature range between –20 to +90^{o}C, the relative permittivity was found to vary from 1.3 to 910000 and the loss tangent from 0.005 to 89. For the same density, a frequency range of 100MHz to 10GHz and a temperature of 20^{o}C, these parameters were found to vary respectively between 1.4-7.6 and 0.014-0.53.

In cases where literature does not include measurements at specific frequencies, a modified form of the Debye equations [19] can be used to calculate the complex electrical permittivity of oven dry wood at any frequency and density (20°C to -70°C) [16].

In cases where experimental measured data is not available for both polarisations, experimentally derived equations can be used to derive the missing information provided one of the two polarisations has been measured.

Other empirical formulas derived from measurements can be also used to estimate the electrical permittivity and the loss tangent for different wood densities as a function of changing temperature and moisture content up to the GHz range.

Apart from solid wood boards, other important wood based materials used in buildings are fibreboards and particleboards. Fibreboards are composed of wood chips or plant fibres bonded together and compressed into rigid sheets. During the production of fibreboards the wood is subjected also to thermal and moisture treatment. All these processes affect the dielectric properties of fibreboards. Classification of fibreboards falls under one of the following categories: Noncompressed with a density of 0.1-0.4g/cm^3, Compressed of medium density of 0.4-0.8 g/cm^3, hardboards having a density of 0.8-1.2g/cm^3, and compressed hardboards with a density of 1.25-1.45g/cm^3.

The dielectric properties of fibreboards will also vary depending on their density, moisture content, wood type, temperature frequency and electric field orientation. The relation between the dielectric properties of oven-dry fibreboards and wood can be estimated by comparing their properties at different frequencies and assuming that the fibres in the fibreboard are parallel to the sheet plane. This allows the direct comparison of dielectric parameters for wood and fibreboards through the tables presented in the literature, where the electrical field is applied perpendicular to the longitudinal axis of the wood under investigation.

Similar to fibreboards are particleboards, which are made of wood fragments and are mechanically pressed into sheet form and bonded together with resin. In the particleboard case, dielectric properties depend also on the kind of resin used during the particleboard construction process [16].

IV. CONCLUSIONS

Information presented in this paper is important since deterministic models should utilise the constitutive parameters presented in the literature in a sensible way. When possible, formulas presented in the literature can be used to theoretically calculate the missing parameters. If the constitutive parameter information is not accurate, prediction errors can accumulate. Examining a range of reported data on different materials and chemical compositions is of prime importance because it reveals the variation trend. This can allow quick and sensible assumptions to be made for any missing values.

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