ASSESSMENT OF DIELECTRIC MODELS AND THEIR APPLICATION TO POLYMER MATRIX COMPOSITES

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ABSTRACT

Assessment of Dielectric Models and Their Application to Polymer Matrix Composites

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The effect of hollow ceramic spheres embedded in the epoxy matrix on the dielectric behavior of composite was investigated in the 100 Hz to 100 kHz range. It was found that the dielectric constant of epoxy matrix can be reduced by mixing the matrix with hollow ceramic spherical inclusions. To predict the effective dielectric constant of the composite, effective medium theory based on Clausius - Mossoti equation was used. It was found that predictions for effective permittivity, based on this relation, correlate well with experimentally obtained results in the entire frequency range of investigation.

To compensate for the degradation of the mechanical properties of the epoxy matrix, which resulted from the incorporation of the spheres into the structure, E-glass fibers, at low fiber volume fraction, were added. The dielectric response of the epoxy-ceramic spheres- glass fibers system was studied, and it was found that this type of composite structure can be used to produce materials with tailored dielectric properties.

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List of Symbols

ε^*	Complex permittivity (complex dielectric constant)
ε'	Dielectric constant
ε''	Loss factor
D	Flux density field (Displacement field)
E	Applied electrical field
E'	Local electric field
$\tan\delta$	Loss tangent
ε_0	Permittivity of the free space
Q	Charge at the condenser plates
ε'_{eff}	Effective dielectric constant (composite media)
ε''_{eff}	Effective loss factor (composite media)
$\tan\delta_{eff}$	Effective loss tangent (composite media)
P	Polarization vector
$\bar{p}$	Dipole moment
ε'_i	Dielectric constant of the i^{th} constituent in the mixture
V	Applied voltage
I_c	Charging current
I_l	Loss Current
α	Polarizability
χ	Electric susceptibility
N	Number (of particles)
a_i	Prager's coefficients (partial derivatives)
f_i	Volume fraction of the i^{th} component in the mixture
ρ	Density
κ^*	Relative complex dielectric constant ($\varepsilon^*/\varepsilon_0$)
κ'	Relative dielectric constant ($\varepsilon'/\varepsilon_0$)
κ''	Relative loss factor ($\varepsilon''/\varepsilon_0$)
ω	angular frequency
f	Frequency of the applied field
G	Conductance
d	Length
r	Radius
ψ	Potential

CHAPTER 1

1. Introduction

1.1 Definition of Complex Dielectric Constant

Engineering materials, based on their electrical properties can be divided into four distinct categories according to the purpose they serve: (1) conductors, (2) semiconductors, (3) magnetic materials, and (4) electrical insulating materials - dielectrics.

A dielectric is a medium or material that maintains an electric field with little supply of energy from outside sources. If a dielectric material is inserted into an electric field it will become polarized, and the flux density of the electric field at the position of the dielectric material insertion will change. The flux density field, D, and applied field, E, in the ideal dielectric material (dielectric with no electrical losses) are related through the following relation:

$$D = \varepsilon' \cdot E \qquad (1.1)$$

where ε^{*} designates the dielectric constant of such a material.

Dielectric properties of any real dielectric material can be described by the dielectric constant, which is a complex quantity. In dielectric analysis and electrostatics the following notation is used for complex dielectric constant, ε^{*},

$$\varepsilon^{*} = \varepsilon^{'} - j \cdot \varepsilon^{''} \qquad (1.2)$$

The real part ε' defines insulating properties, and the imaginary part ε'' describes conductive properties of the dielectric material. Conductivity exists in all real dielectrics and it is used to measure the effectiveness of the dielectric material. To describe the complex nature of the dielectric constant, one would have to consider a dielectric material being placed between the electrodes of a parallel plate condenser attached to a sinusoidal voltage source where loss and charging currents develop. In this thesis, the dielectric properties are described by the real part of the complex dielectric constant (ε') and the loss tangent (tan δ) which is expressed as:

$$\tan\delta = \frac{\varepsilon^{''}}{\varepsilon^{'}} \qquad (1.3)$$

1.2 Research Objectives

The dielectric properties of a material are of great concern for telecommunication applications. Since the signal propagation delay time is proportional to the square root of the dielectric constant of the transmitting medium, a low dielectric constant is often desirable. For example, high-speed integrated packages require materials with dielectric constant lower than 3.5, whereas, satellite communication applications require materials with a dielectric constant of 2.5, in addition to a low loss tangent.

Rexolite, a polystyrene based thermoplastic material is used for lens and rod antenna applications for satellites. A typical antenna is shown in Fig. 1.1. Rexolite has excellent dielectric properties. Its mechanical and physical properties, however, are less satisfactory. The properties for Rexolite 1422 are given in Table 1.2.

The ideal material for antenna application would have similar dielectric properties to Rexolite but a lower coefficient of thermal expansion (CTE), a higher toughness and the lowest possible density. Since these properties cannot be obtained from a natural material, artificial dielectric materials must be developed.

Artificial dielectrics can be made through the route of synthesis or composite. By synthetic process, the properties of a material are tailored to order by combining the proper atoms and molecules into specific arrangement. By composite method, a material with desired properties is obtained by combining different materials. Because the required compatibility between dissimilar materials is more relaxed, as compared with that required at atomic and molecular level, composite method is more versatile and hence can produce new materials with a much wider range of properties than those produced by the synthetic method.

To develop composite materials with tailored properties, one should be able to predict a property of a composite based on the properties of its constituents. Such relationships have been well established for the prediction of elastic constants, density and other thermal, mechanical and physical properties. For dielectric properties, however, less work has been done. Based on a literature survey, there are several mathematical models available that have been verified with ceramic based composites. The applicability of these models to polymer based composites, however, is not known and hence requires further investigation.

The ultimate goal of this work is to develop artificial dielectric materials with dielectric, mechanical and physical properties required by Spar using composite methods. As a first stage, this thesis focuses on the evaluation of available models for the dielectric properties of composites and their applicability to polymer based composite systems. A model composite, epoxy based composite is used for this evaluation. Table 1.1 summarizes several possible applications for artificial dielectrics.

APPLICATION	FREQUENCY RANGE [GHz]	DIELECTRIC CONSTANT [-]	LOSS TANGENT [-]
Lens	10 - 20	2.54	<0.0001
Rod Antenna	10 - 20	2.54	<0.0001
Patch Antenna	10 - 20	3 - 6	<0.00012

Table 1.1 Electrical requirements for satellite communications. applications (source : Spar Aerospace Ltd.)

The objectives of the present work consist of the following :

- Development of the epoxy/ceramic sphere system and epoxy/ceramic sphere - glass fiber system with tailored (reduced) dielectric constant for the evaluation of the existing dielectric models.
- Assessment of the existing dielectric models for heterogeneous media, and their applicability to the polymer matrix composites.
- Experimental dielectric data collection for epoxy matrix composites, reinforced with E-glass fibers and hollow ceramic spheres in the 100 Hz to 100 kHz range.

Dielectric analysis and modeling of the epoxy/ceramic sphere system and epoxy/ceramic sphere -glass fiber system conducted in the present work, to the author's knowledge, is the first of its kind. It will hopefully contribute towards achieving a better understanding of dielectric behavior of polymer matrix composite materials.

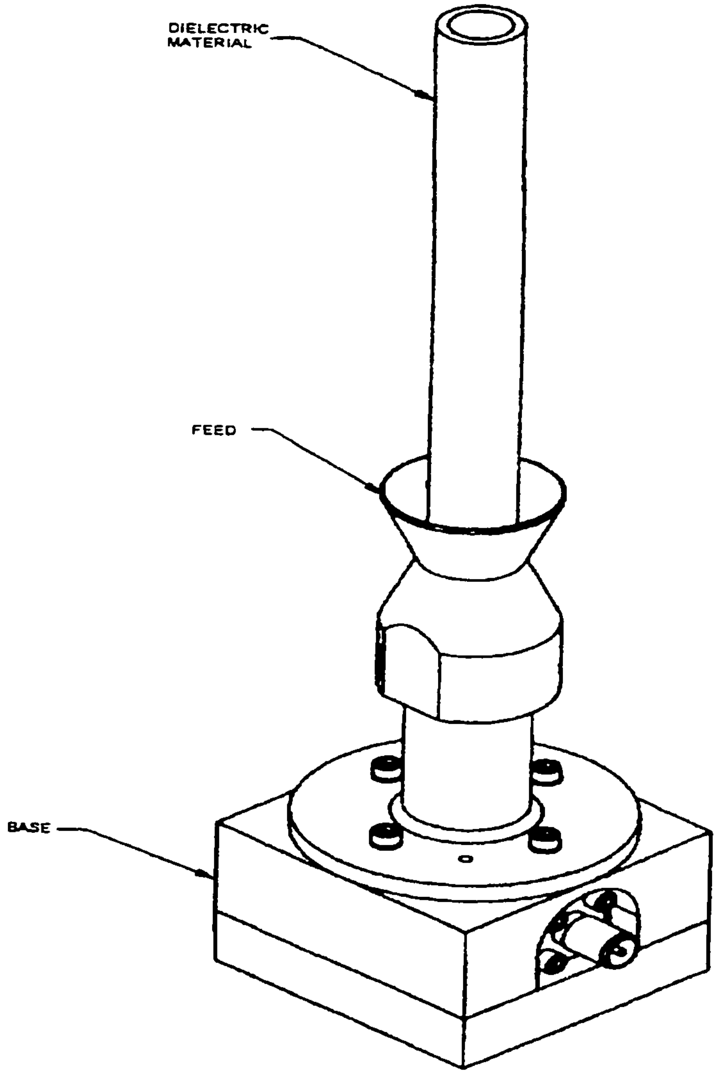

Figure 1.1 Dielectric Rod Antenna

ELECTRICAL:		
Dielectric constant at:	1 [MHz] - 500 [GHz]	2.53
Dissipation factor at :	1 [MHz]	0.00012
	10 [MHz]	0.00025
	10 [GHz]	0.00066
Volume Resistivity [Ohm-cm]		$>10^{16}$
Surface Resistivity [Ohm]		$>10^{19}$
Dielectric Strength - step by step [V/Mil]		500
PHYSICAL		
Specific Gravity [gr/cm^3]		1.05
Tensile Strength [psi]		9000
Flexural Strength [psi]		11500
Impact Strength - room temp. to 75 °C [Ft. lb./ in. of notch]		0.3
Coefficient of thermal Expansion [/°C]		7.0×10^{-5}
Thermal Conductivity [cal/Sec/ cm^2/ °C /cm]		3.5×10^{-4}
Recommended operating range [°C]		-60 to +100
Acoustic impedance [-]		2.5
velocity of sound [m/s]		2362.2
CHEMICAL		
Water Apsorbtion (Max) [%]		0.05
Alkalis (Sodium / Potassium Hydroxide)		No effect
Alcohols (Methanol / Isopropanol)		No effect
Aliphatic hydrocarbons		No effect
Aromatic hydrocarbons		Swells
Chlorinated Hydrocarbons		Swells
OPTICAL		
Visible light 1" thick		87 %
Refractive index 589		1.590
Refractive index 486		1.604
Refractive index 656		1.585

Table 1.2 Rexolite 1422 Properties Chart.
(Data source: C-Lec Plastics Inc.)

CHAPTER 2

2. Mechanisms of Polarization in Solid Dielectrics

A dielectric material can react to the applied electric field because it contains charge carriers that can be displaced. On the macroscopic scale the mechanism of polarization can be explained by investigating the surface charge distribution on the plates of a condenser connected to a voltage source [Fig. 2.1]. Dielectric medium inside the condenser will become polarized by the electric field E, by means of the alignment of electric dipoles contained in the dielectric material. In electrostatics, an electric dipole is defined as an entity in which equal positive and negative charges are separated by a small distance, forming an electric dipole moment [Figure 2.2 a]. Exposed to the applied electric field , electric dipoles will tend to align themselves in the direction of the field [Figure 2.2 b]. In the parallel condenser, with voltage source applied, all the dipole ends of the opposite charge inside the dielectric material will be neutralized. However an uncompensated surface charge will remain, negative at the top, positive at the bottom plate (or vice versa depending on the applied source direction). Respecting the laws of electrostatics, the electric field between the plates must be proportional to the voltage applied regardless whether the dielectric is present or not. With the presence of the dielectric material in the condenser, some of the surface charges on the plates are neutralized by being bound by the dipole ends. Therefore, the required magnitude of the electric field E, can be maintained only if more charges flow from the applied voltage source. Thus resulting in an increase of charge density $Q^{\cdot}$ at the condenser plates, of which some are bound and thus do not contribute to the electric field [Figure 2.1].

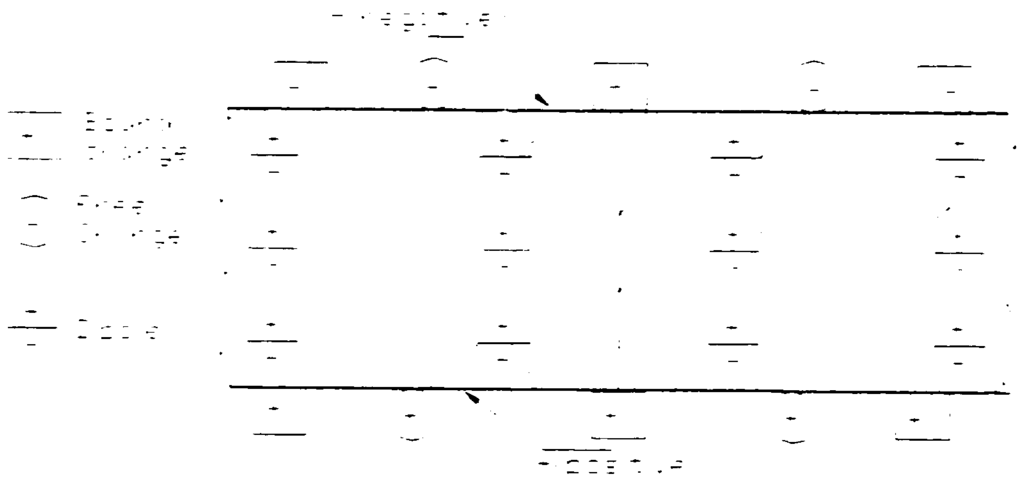

Figure 2.1 Polarization in dielectric (macroscopic view) [3]

The amount of charge at the plates Q' can be expressed as: $Q' = Q + Q_B$, where charge designated as Q_B is the bound charge density and Q is the initial charge. Taking into account the bound charges, the density of the flux lines (also known as electric displacement field D) is expressed as:

$$D = \varepsilon_0 \cdot E + Q_B = \varepsilon_0 \cdot E + P \qquad (2.1)$$

where the bound charge is called polarization vector and usually in electrostatics is designated as P and ε_0 is the permittivity of the free space. For many dielectric materials, polarization is related to the applied field through the relation [7] :

$$P = D - \varepsilon_0 \cdot E = (\varepsilon' - \varepsilon_0) \cdot E \equiv \chi \cdot \varepsilon_0 \cdot E \qquad (2.2)$$

The factor $\chi = \dfrac{P}{\varepsilon_0 \cdot E} = \kappa' - 1$ is known as electric susceptibility of the dielectric material, and $\kappa' = \dfrac{\varepsilon'}{\varepsilon_0}$ is the relative dielectric constant.

The polarization vector, P, is also equivalent to the dipole moment per unit volume of the material [3]. The dipole moment per unit volume can be thought of as resulting from the additive action of elementary dipole moments $\bar{p}$:

$$P = N \cdot \bar{p} \qquad (2.3)$$

Where N is the number of elementary particles per unit volume. The dipole moment of the elementary particle, furthermore, is assumed to be proportional to the local electric field strength, E', that acts on the particle [5]:

$$\bar{p} = \alpha \cdot E' \qquad (2.4)$$

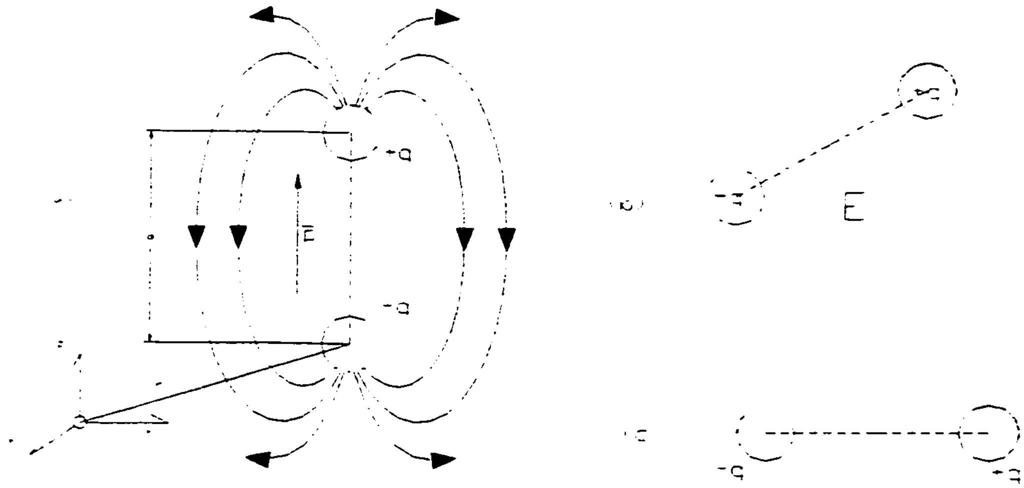

Figure 2.2 (a) Electric dipole (b) Alignment of a dipole (c) Final dipole alignment with the field

The proportionality factor, α , is called polarizability and it measures the average dipole moment per unit field strength. Based on previous equations the polarization can be expressed as:

$$P = \left(\kappa' - 1\right) \cdot \varepsilon_0 \cdot E = \cdot N \cdot \alpha \cdot E' \qquad (2.5)$$

which links the macroscopic measured permittivity to the three molecular parameters: the number of contributing elementary particles per unit volume, N; their polarizability, α ; and the locally acting electric field, E'.

This field (E') will normally differ from the applied field E, owing to the polarization of the surrounding dielectric medium. It is the objective of the molecular theories to evaluate all these parameters and thus to arrive at an understanding of the phenomena of polarization and its dependence on frequency, temperature and applied field strength.

In the dielectric analysis of composite materials investigated in this thesis, three mechanisms of polarization are observed:

1. Electronic polarization
2. Ionic polarization
3. Dipole (Orientational) polarization

Each mechanism is investigated separately, and its effect on the overall polarization vector, P, is evaluated.

2.1 Mechanism of Electronic Polarization

Matter electrically speaking consists of positive atomic nuclei and negative electron clouds. Upon application of an external electric field the electrons are displaced slightly with respect to the nucleus [Figure 2.3]; Induced dipole moments cause the electronic polarization of the material.

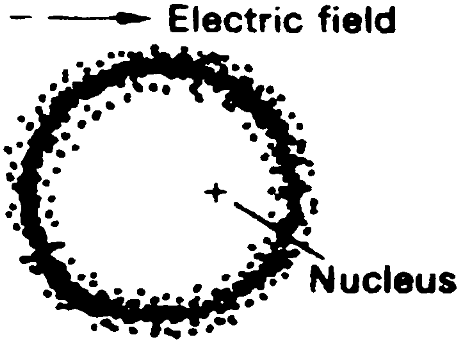

Figure 2.3 Electronic polarization [3]

Electrons of the inner atomic shells have critical frequencies higher than 10^{19} [Hz] (X-ray range) for most engineering materials. Consequently, an electromagnetic field of a frequency higher than $\approx 10^{20}$ [Hz] cannot excite any vibration in the atoms; hence it has no polarizing effect on the material, which has for this frequency the same permittivity as a vacuum ($\frac{\varepsilon'}{\varepsilon_0} = 1$) [Figure 2.4]. For frequencies higher than $\approx 10^{20}$ [Hz], the relative permittivity is close to unity. If the frequency of the applied electromagnetic field is lower than the resonant frequency of the electrons in the inner shell of the atom, these electrons can vibrate with the applied field, polarizing the material in that respect. Electronic polarization gives rise to the relative permittivity above the unity. When the frequency of the applied electromagnetic field is in the range of 10^{14} - 10^{15} [Hz] (optical range to U.V. range) valence electrons take part in the overall dielectric polarization of the material and relative permittivity rises [Figure 2.4]. For dielectric materials exhibiting electronic polarization as the only type of polarization, the dielectric constant is independent of frequency for frequencies less than 10^{12} Hz. For this type of polarization, the displacement of electrons is purely elastic in nature, and as soon as the electric field is removed, as during the discharge of a capacitor, the electrons return to their initial (non applied field) normal state positions. The entire process takes place without irreversible energy absorbtion in setting up the electric field which causes electric polarization i.e. the energy of a charged capacitor is fully released on discharge. Consequently, electronic polarization gives rise only to the charging current component .

Electronic polarization decreases with the rise of temperature due to thermal expansion. This dependence is determined by the magnitude of the temperature coefficient of the dielectric.

$$\alpha_e = \frac{1}{\varepsilon} \cdot \frac{d\varepsilon}{dT} \left[{}^0C^{-1} \right] \qquad (2.6)$$

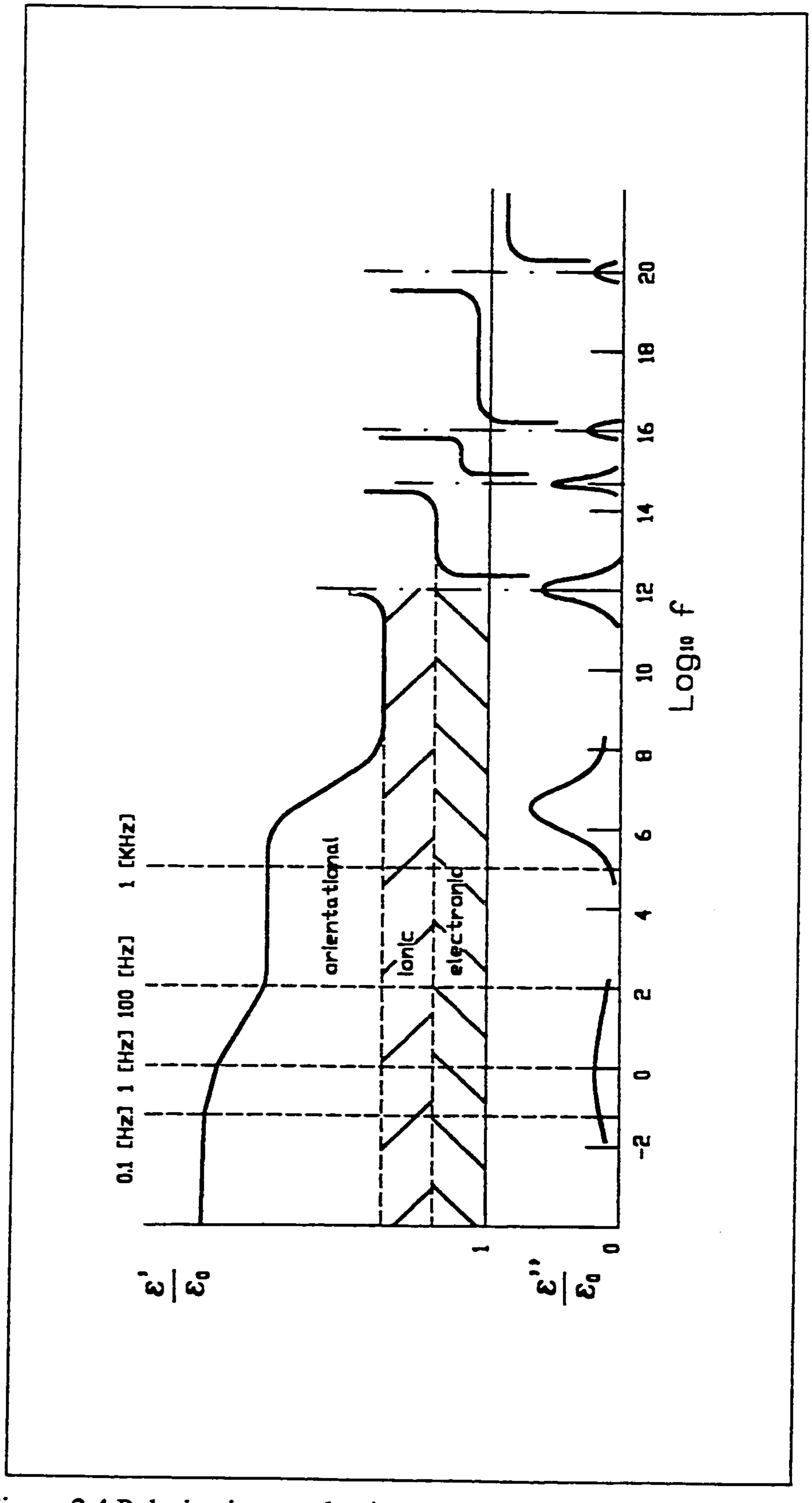

Figure 2.4 Polarization mechanisms versus frequency in dielectric material

2.2 Mechanism of Ionic Polarization

Certain dielectric materials may undergo another type of polarization in addition to electronic polarization. This type of polarization is called ionic and it also does not give rise to a loss current. Ionic polarization, which is characteristic of ionic crystals, consists of displacement of ions brought about by an applied electric field. The positive ions are shifted in the direction of the negative electrode and positive ions in the direction of the negative electrode. Displacement from the equilibrium position existing in the absence of the applied field is inherently small and like in the case of electronic polarization being elastic in nature, gives rise only to charging current which supplements that contributed by electronic polarization. Since the currents resulting from the ionic polarization and electronic polarization are in phase, a dielectric in which these two components are set up will give greater capacitance resulting in higher dielectric constant. Ionic polarization time is greater than electronic, due to the much greater mass of the ions. Most dielectric materials experience ionic polarization in the frequency range of less than 10^{13} [Hz]. Like in the case of electronic polarization, the dielectric constant associated with the ionic polarization is independent of frequency [Figure 2.4] for frequency less than 10^{12} Hz.

Dielectric materials subjected to intense ionic polarization have a dielectric constant associated with the positive temperature coefficient. This can be attributed to a weakening of the elastic forces that act upon the ions at the crystal lattice points under the effect of temperature rise, and also to increased thermal motion, both making for greater ion displacement on application of an external electric field. Although temperature increase causes thermal expansion, and thus leads to a certain decrease in electronic polarization, in most materials this effect is less pronounced than the increase in ionic polarization due to the rise of temperature and therefore the net dielectric constant increases with temperature rise.

2.3 Dipole (Orientational) Polarization

The structure of the molecules has a strong influence on polarization processes. In many dielectrics the molecules contain an inherent electric dipole moment even in the absence of the electromagnetic field. Such molecules have the centers of their positive and negative charges displaced with respect to each other and therefore form a dipole. These molecules are called polar molecules. When an electric field is applied to materials containing polar molecules another type of polarization occurs in dielectric called orientational or dipole polarization. Upon applying the field to polar dielectrics, dipoles experience tension due to the existence of electromagnetic field. The distance between the centers of the positive and negative charges becomes greater and the dipole moment increases. The electric field forces a certain reorientation of the dipoles. The dipoles rotate, so that the positively charged ends face negative electrode and the negative dipole ends face positive electrode. The tension to which the dipoles are subjected, as well as, their orientation in the field corresponds with the direction of the displacement electrons contributing to the electronic polarization. Oriented dipoles increase the overall dielectric constant of a material [Figure 2.4]. Orientational polarization will be more intense as the dipole moment of the molecules increase.

The dependence of dielectric constant and loss tangent on the frequency and temperature is shown for several engineering materials in Figures 2.5 and 2.6.

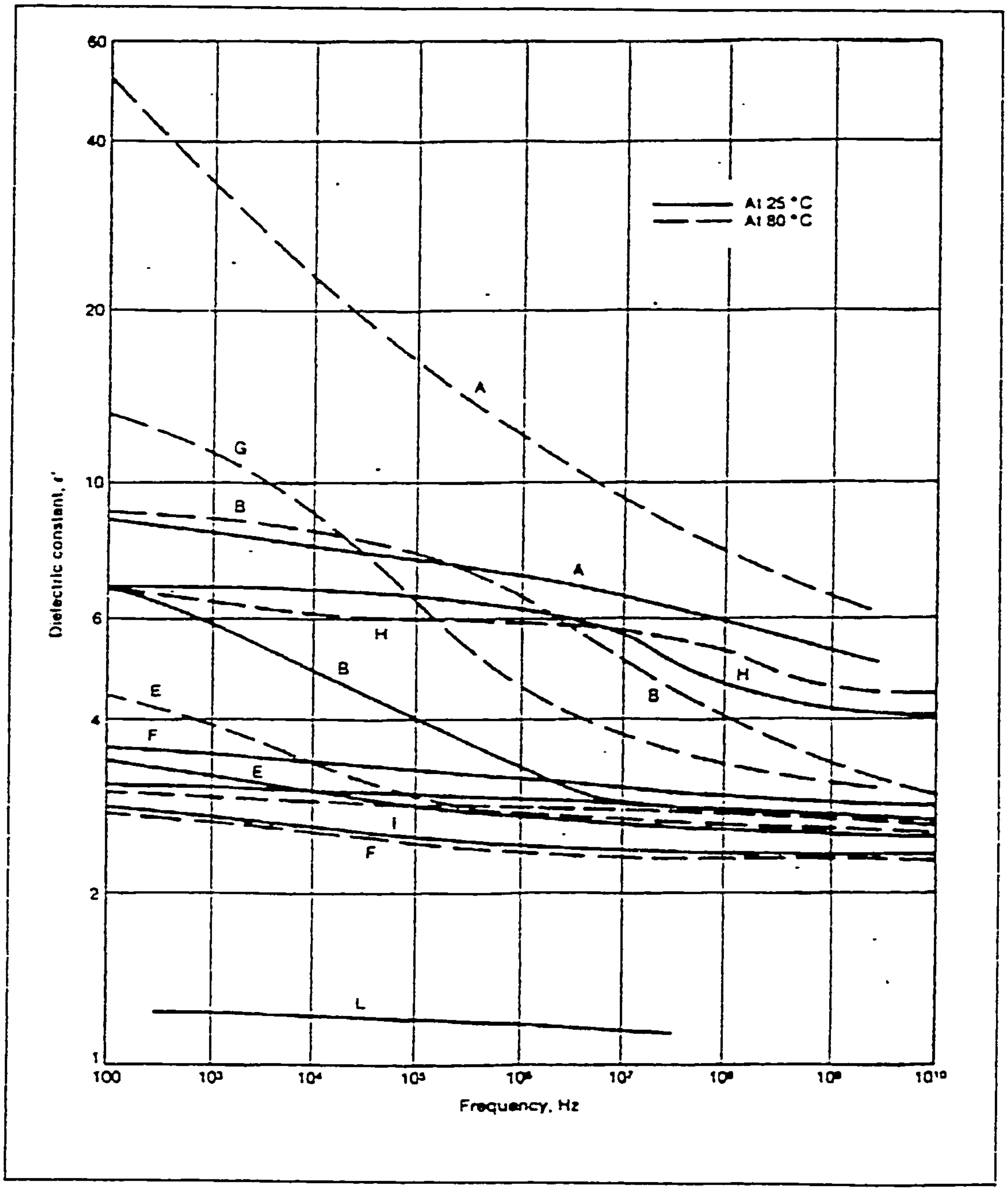

Figure 2.5 Dielectric constant vs frequency and temperature **A** clear cast phenolic resin, **B** plasticized PVC, **E** polymethyl methacrylate, **F**, polychlorotrifluoroethane, **G** nylon, **H** neoprene, **I** plasticized ethylcelluloze, **L** polyurethane foam (0.033 gr/cm^3), [34]

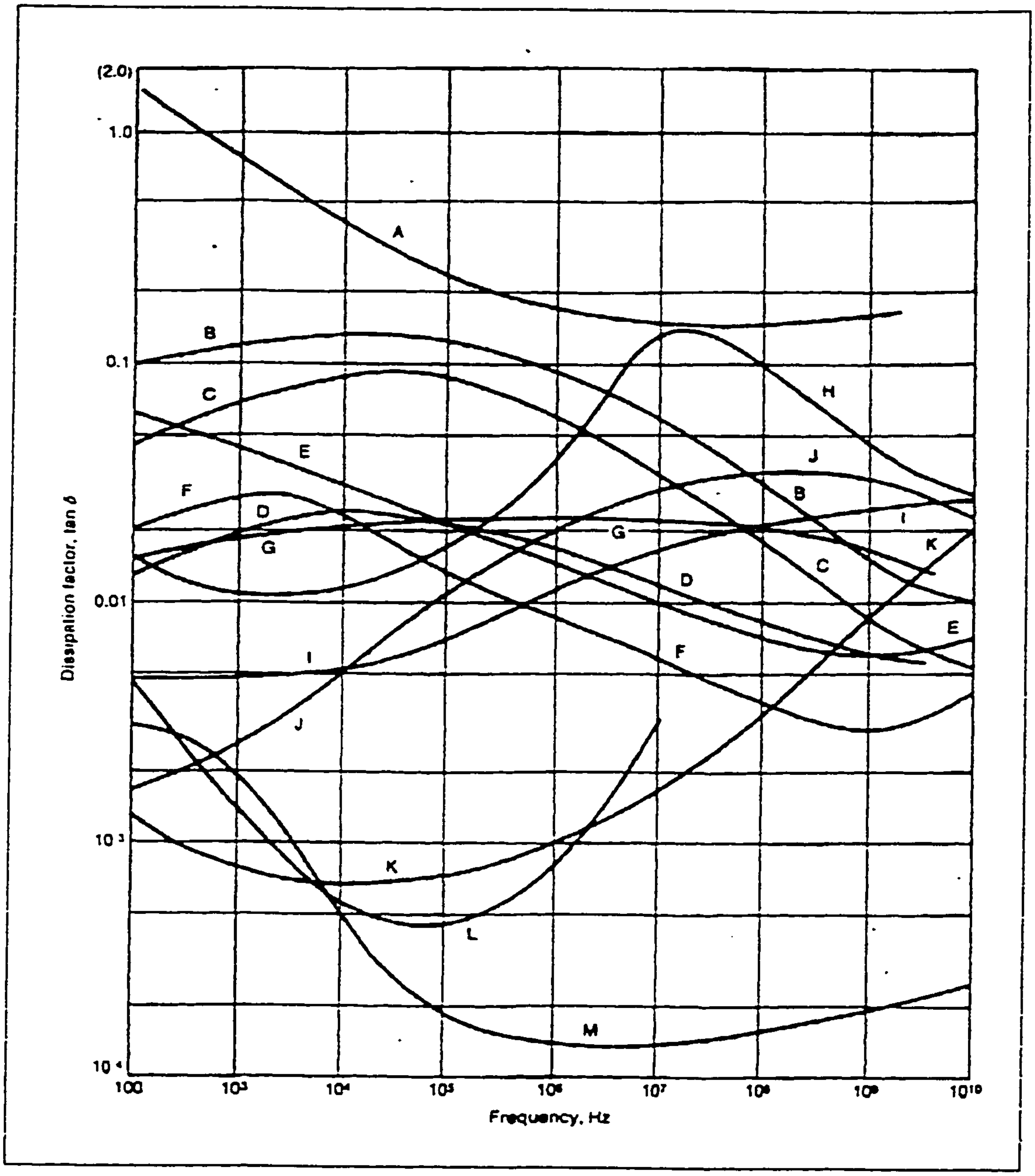

Figure 2.6 Loss tangent vs frequency and temperature **A** clear cast phenolic resin, **B** plasticized PVC, **C** polyvinyl chloride, **D** unplasticized PVC, **E** Polymethyl methacrylate, **F** polychlorotrifluoroethane, **G** nylon, **H** neoprene, **I** plasticized ethylcelluloze, **J** epoxy cast resin, **K** silicone rubber, **L** polyurethane foam , **M** polystyrene, **L** polyurethane foam. [34]

2.4 Dielectric Behavior of Epoxy Resin

In polymer materials polar groups can be attached to either the main polymer backbone or to the side groups. If the polar molecules are attached to the backbone complete polar orientation is not possible upon application of an electric field because of the spatial constraints imposed by the structure. Polymer chains are often coiled and entangled and the time required for dipole orientation is a function of the chain entanglement. When the dipoles are attached to the backbone their movement depends on the ability of the chain segments to move. The dipole polarization effect is much lower below the glass transition temperature (T_G). If the polar groups are attached to the side group on the backbone, segmental motion of the chain segments is not essential for the groups to orient [Figure 2.7].

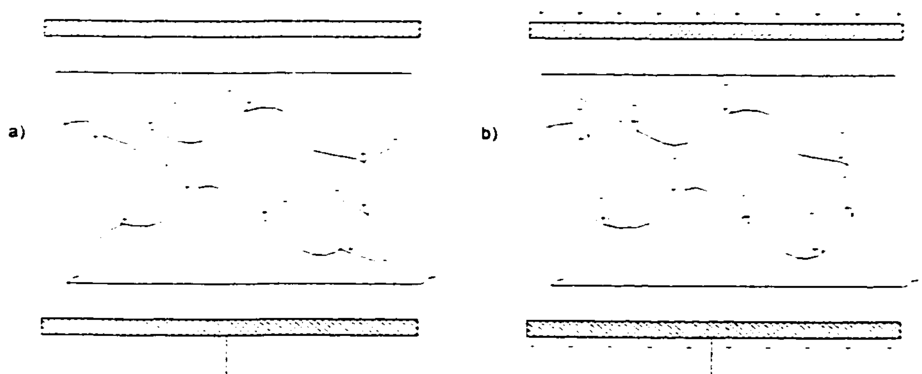

Figure 2.7 Dipole orientation, attached to side groups

In the case of dipoles that are attached to the side groups on main polymer backbone it is possible to contribute to the overall polarization vector, P, even below the glass transition temperature (T_G). Orientation of the dipoles is not purely elastic as it is in the case of ionic or electronic polarization. Orientation of the dipoles involves overcoming certain friction forces on which a certain amount of irreversible energy has to be expanded and is dissipated as heat.

Dependence of dielectric constant and loss tangent for polar dielectrics on frequency and temperature is a complex function. Temperature rise has a dual effect on dipole polarization: (a) due to weakening of the intermolecular forces the dipole orientation is enhanced, and (b) at the same time due to the intensified thermal agitation , the dipole polarization is reduced , because the orientation of the dipoles or molecules is more strongly disturbed by the strengthened chaotic thermal agitation.

The dielectric constant of a polar dielectric is dependent on the frequency of the applied electromagnetic field. Up to a certain frequency the dielectric constant remains practically constant, but at the frequency exceeding a certain value (depending on material composition) the lower value is invoked by only electronic and ionic polarization. Above this frequency, molecules, owing to their great mass, are unable to orient themselves fully to the applied field each time. This lowers the overall value of the polarization field in the dielectric.

Effect of the orientational polarization on the dielectric properties of several types of epoxy resins, commercially available today, is compared to the other engineering materials and it is summarized in Table 2.1.

Thermosetting resin (Epoxies)	Dielectric constant	Loss tangent
DERKANE 411-45	3.38	0.003
DERKANE 411-C-50	3.32	0.022
DERKANE 470-36	4.58	0.008
CIBA 6020	3.41	0.018
ERL3794	3.27	0.027
Thermoplastics		
Silicone	3.00-7.00	0.0005-0.002
Nylon	3.60-5.00	0.010-0.040
ABS	2.50-3.50	0.010-0.040
Polyethylene	2.30	0.0001-0.0005
Polystyrene (at 30 -60 GHz)	2.54	0.00012-0.00066
Ceramics		
Alumina Ceramic	8-10	
Silicon nitride	9.4	
Mulite	6.50-7	

Table 2.1 Comparative dielectric properties of epoxies with other engineering materials at room temperature and 1 kHz.(Source: supplier data)

In the present study, an epoxy based on diglycydil-ether of bisphenol A (DGEBA) is studied. An analysis of the chemical structure [Figure 2.8] of this type of epoxy indicates the existence of highly polar groups. These are capable of inducing orientational polarization which results in high values of dielectric constant when compared to non-polar structures.

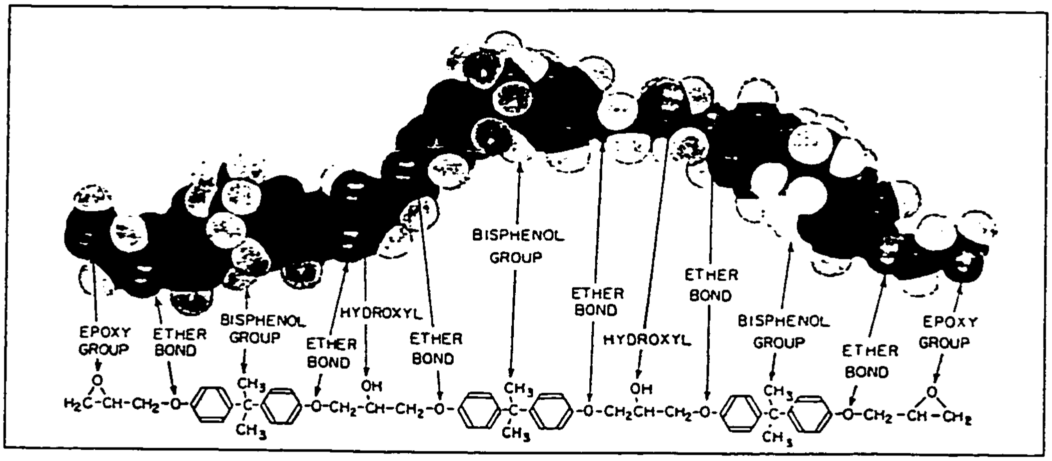

Figure 2.8 Atom model of epoxy-resin DGEBA molecule [36]

The curing agent has significant importance on the final dielectric properties of the cured epoxy resin. The three most common curing agents (for epoxy resins) used in engineering practice, are: anhydride, aromatic amines and Lewis acid. The effect of these three curing agents on the dielectric properties of DGEBA epoxy is presented in Table 2.2.

In the present work the cycloaliphatic amine was used as a curing agent for DGEBA epoxy resin. The DGBEA resin cured with cycloaliphatic amine gives high temperature stability of the dielectric constant up to 80 °C with a small increase in the loss tangent within the same temperature range [Figure 2.9].

Curing Agent	Anhydride NMA	Amine MDA	Lewis Acid BF_3
Dielectric constant			
60 Hz	3.15	4.10	3.47
10^3 Hz	3.14	4.06	3.45
10^6 Hz	2.97	3.56	3.23
Loss tangent			
60 Hz	0.0020	0.0054	0.0029
10^3 Hz	0.0054	0.015	0.0053
10^6 Hz	0.017	0.036	0.0230

Table 2.2 Cured resin properties of standard DGEBA epoxy resin using different curing agents. (Source: supplier data)

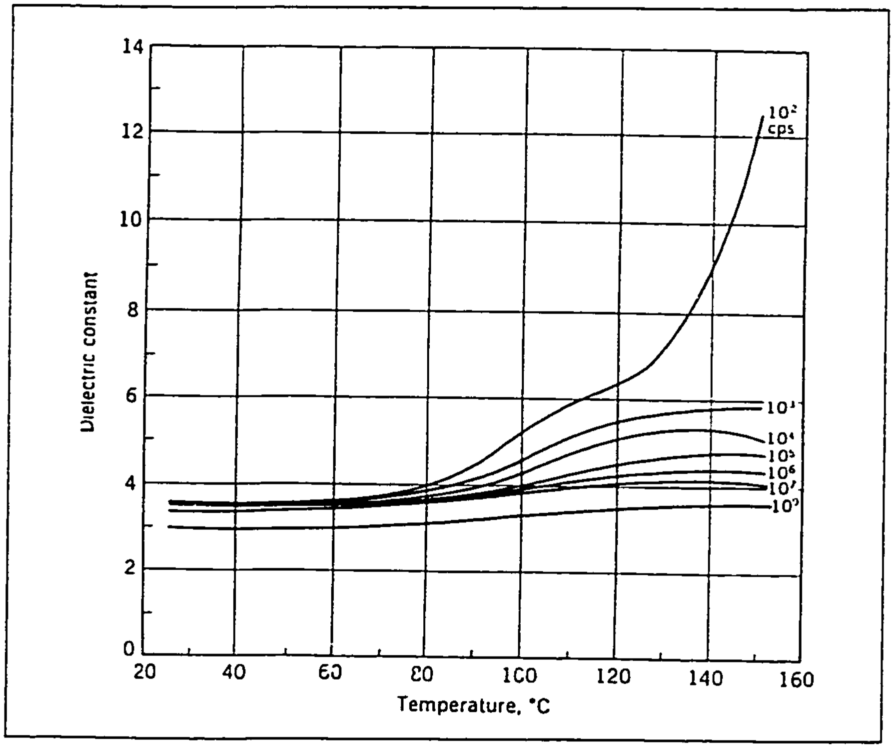

Figure 2.9 Dielectric constant of cycloaliphatic amine cured DGEBA epoxy resin [36]

CHAPTER 3

3. Literature Overview

(Dielectric models for ceramic matrix composites)

The composite material can be defined as an inhomogeneous medium consisting of at least two different substances. Study of the electric properties of composite media began more than 100 years ago when many well known scientists attempted to develop molecular field concepts in dielectric theory. Despite the long history of research effort and abundance of literature on the subject of the composite materials, only in a certain special cases have some theories been successful in predicting the effective electrical properties of some composite media. Generally speaking, for two-component dilute solutions or sparse mixtures in which one component has a much smaller volume than the other , the effective dielectric constant can be accurately predicted from the Clausius - Mosotti relation [6, 7], This relation was also obtained by Maxwell, Lorentz-Lorentz, Garnett, Wiener and Wagner [6]. One of the first relations describing a composite material dielectric behavior based on the dielectric properties and volume fractions of its constituents was given by Von Bruggeman [8]. For years, various dielectric models for heterogeneous mixtures have been explored. Summaries of these dielectric mixing formulae can be found in the literature [10]

Using effective medium theory based on the Clausius - Mossoti relation, Jay G. Liu and David L. Wilcox [9] predicted the effective dielectric constant for a cordierite matrix (2MgO, $2Al_2O_3$, $5SiO_2$) loaded with hollow ceramic sphere inclusions. The validity of simple effective medium theory based on Clausius equation and relations developed by Maxwell-Garnett and Bruggeman was studied in [4]. In this study the zirconia - alumina ceramic (ZrO_2 , Al_2O_3) composites were subjected to 15 - 140 [GHz]. One of the constraints of the effective medium theory based on the Clausius - Mossoti relation is that it is valid only for dilute suspensions. With high volume fractions of inclusions in the host medium the effects of local field become more apparent and this theory fails to predict the effective dielectric constant since it assumes no field interactions between inclusions. Using the boundary integral method to solve Laplace equation B.Sareni et al. [11] developed a numerical procedure that accurately predicts effective dielectric properties of composite structure even for high values of inclusion loading. This method is applicable for any shape inclusions and to high ratios of permittivities of the constituents.

The theoretical influence of particle shape on dielectric properties of composite materials was studied in [12, 13], Particle shape influences the dielectric properties of composite materials in two ways: it determines the polarizability of the individual, isolated non-spherical particles; and it determines the critical packing fraction. By considering the additional effective particle shape factor , W.T Doyle and S.Jacobs [12] developed a cluster model to determine effective polarizability of the composite. They experimented with Ni-Cr alloy, and compared experimental results with the classical Clausius - Mossoti relation. The cluster model was in close agreement with experimental results for mono-disperse suspensions of spheres and produced enhancements over the classical approach taken by Clausius - Mossoti. Experimental permittivity data for Zinc and Aluminum particles in a paraffin wax matrix (κ'=2.25) was obtained by Kelly and coworkers [4] at 9364 [MHz]. The collected data was used by W.T Doyle and S.Jacobs [12] to validate the cluster model for these types of composites and to compare it to Clausius - Mossoti and Wiener equations. Wiener O. [14] calculated the bounds for the effective permittivity of the composite material in terms of dielectric constants and volume fractions of constituents. The advantage of the Wiener approach is that the model is applicable to the two-phase composite materials (statistically isotropic) regardless of composition or microstructure. These bounds are absolute bounds in dielectric analysis of composite mixtures [5], [17]. The disadvantage of the Wiener model is that it may yield wide bounds depending on the ratio of relative permittivities of the mixture's constituents. Bounds set by Wiener were improved by Hashin and Shtrikman [15]. Using Hashin and Strikman's equations, Stepanow [16] predicted bounds for conductivity of Mg_2Pb - Pb mixture and confirmed the predicted results with experimental data. Initial bounds calculated by Wiener, yielded a wider envelope for this system. It is interesting to note that DeLoor, as found in [17], on the basis of extensive experimentation, alone, speculated that the bounds set by Hashin and Stirkman were the bounds for the dielectric constant of a dilute suspension of spheres, even before these bounds were theoretically established.

The dielectric constant of fiber reinforced composites was analyzed by Hashin [17] for a transversely isotropic fiber reinforced material having two principal dielectric constants, in the fiber direction and normal to the fibers. In his research, using cylinder assemblage model, Hashin calculated the dielectric constant for fiber reinforced composite materials in terms of the dielectric properties and volume fractions of composite constituents.

A very important property of a dielectric material is its loss factor. Hashin and Schulgasser [18] derived bounds for the loss factor of composite materials composed of lossy constituents. The derivation of the bounds considers that the imaginary part of the complex permittivity is small in comparison to the real part. For polymer materials, this assumption is correct [Figure 2.5 and Figure 2.6]. Depending on the ratio of the constituents loss factors, this theory may yield wide bounds unacceptable from a practical engineering point of view. In general, the higher the ratio of losses of the constituents of the mixture the wider the bounds will be.

The mechanical behavior of a solid microsphere filled composite was studied by T.G.Richard [21]. The objective of this research was to produce an analytical relationship between the constituents of the composite system and its overall mechanical response. Based on these analytical results and experiments on solid glass microspheres embedded in a polyester matrix , T.G. Richard suggested following theories to predict the mechanical behavior of microspheres filled composites:

1. Isostrain theory for Elastic Modulus predictions of composite.
2. Isostress theory for Poisson ratio predictions. Also, satisfactory results can be obtained for Elastic modulus predictions using this theory.
3. Hill and Kerner's [24, 25, 26] theory for Shear and Bulk Modulus of the composite.

The mechanical behavior of epoxy matrix filled with graphite inclusions was studied by Whitney [23].

The effects of amine content on the dielectric properties of the epoxy/amine system was studied by M.Finzel and M. Hawley [30]. The dielectric behavior of the mixture (DER332/DDS) was analyzed at 2.45×10^9 Hz within a 50°C to 100 °C temperature range for various epoxy/amine mixture ratios.

3.1 Modeling of Dielectric Properties of Composite Materials

The interaction between electromagnetic waves and dielectric materials is ruled by Maxwell equations [3] over the whole frequency range. These equations describe quantitatively how a time varying electric field is accompanied by a time varying magnetic field, and vice versa.

Since both fields can cause energy storage and energy dissipation in the material, two sets of parameters are required to characterize a dielectric as a carrier of electromagnetic energy. The complex permittivity, ε^*, can be considered a fundamental parameter for the macroscopic description of a dielectric exposed to the alternating fields.

3.2 Complex Permittivity

A capacitor connected to a sinusoidal voltage source,

$$V = V_0 \cdot e^{j \cdot \omega \cdot t} \qquad (3.1)$$

of the angular frequency $\omega = 2 \cdot \pi \cdot f$ stores, when vacuum is dielectric, a charge:

$$Q = C_0 \cdot V \qquad (3.2)$$

and draws a charging current:

$$I_c = \frac{dQ}{dt} = j \cdot \omega \cdot C_0 \cdot V \qquad (3.3)$$

leading the voltage by the temporal phase angle of 90°. C_0 is the capacitance of the condenser. If some other substance is used as a dielectric, the condenser increases its capacitance ,C, to:

$$C = C_0 \cdot \frac{\varepsilon'}{\varepsilon_0} = C_0 \cdot \kappa' \qquad (3.4)$$

where ε' and ε_0 designate the real permitivitties or dielectric constants of the dielectric and vacuum, respectively, and κ' designates the relative dielectric constant of the dielectric material.

When lossy dielectrics are used to increase the capacitance of the condenser the loss current ,I_l, coexists with charging current ,I_c, and is equal to:

$$I_l = G \cdot V \qquad (3.5)$$

The loss current is in phase with the applied voltage. In the preceding equation, G represents the conductance of the dielectric. The total current, I, traversing the condenser is:

$$I = I_c + I_l = (j \cdot \omega \cdot C + G) \cdot V \qquad (3.6)$$

The loss current is inclined by a power factor angle θ (θ<90°) against the applied voltage, V, which is also the loss angle, δ measured against the positive j-axis.

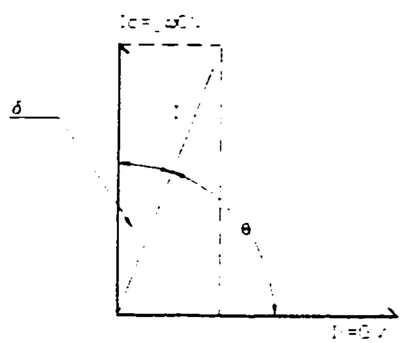

Figure 3.1 Currents in the capacitor containing dielectric with loss

It is customary in electrostatic analysis to refer to a loss charging current by the introduction of complex permittivity:

$$\varepsilon^* = \varepsilon' - j \cdot \varepsilon'' \qquad (3.7)$$

The total current, I, may be rewritten,

$$I = \left(j \cdot \omega \cdot \varepsilon' + \omega \cdot \varepsilon''\right) \cdot \frac{C_0}{\varepsilon_0} \cdot V = j \cdot \omega \cdot C_0 \cdot \kappa^* \cdot V \qquad (3.8)$$

where,

$$\kappa^* \equiv \frac{\varepsilon^*}{\varepsilon_0} = \kappa' - j \cdot \kappa'' \qquad (3.9)$$

is the relative complex permittivity of the matter. Whereas, ε'' and κ'', are the loss factor and the relative loss factor respectively. The loss tangent becomes:

$$\tan\delta = \frac{\varepsilon''}{\varepsilon'} = \frac{\kappa''}{\kappa'} \qquad (3.10)$$

Measurement, prediction and analysis of ε' and ε" for the composite system is of primary interest in this research. These are key to defining and predicting the dielectric behavior of the composite material.

3.3 Effective Permittivity of Composite Media

The concept of effective permittivity, or macroscopic dielectric constant, can be used to describe media that are homogeneous to the extent that scattering effects are insignificant as radio waves penetrate these materials. The effective dielectric constant or the macroscopic permittivity, ε'_{eff}, is defined as the ratio between the average displacement field $\overline{D}$ and the average electric field $\overline{E}$:

$$\overline{D} = \varepsilon'_{eff} \cdot \overline{E} \qquad (3.11)$$

In radio wave propagation problems and remote sensing applications, the typical geophysical media is composed of materials with different dielectric properties. The use of effective permittivity in treatise of these problems has been proven to be very effective. This parameter can be measured and it can be expressed in terms of the constituent properties in experimental formulas.

Using a theoretical approach to assess the effective permittivity of dielectric mixtures requires the calculation of the polarizabilities and dipole moments of the inclusions that compose the mixture. The dipole moments of simple discrete inclusions, like spheres and ellipsoids, can be expressed in closed form and the mixing formula for a two phase mixture can be derived. However, only for dilute suspensions is the mixing rule unique. Given the many degrees of freedom of a random medium for dense mixtures, it is plausible that many rivaling mixing formulas coexist.

The concept of effective permittivity focuses on mixtures where the inclusions are not seen as discrete inclusions but rather the whole mixture is considered to be a continuous random medium.

The concept of effective permittivity is a quality attributable to heterogeneous media. To be able to introduce this concept, the sizes of the inclusions have to be considerably smaller than the wavelength of the operating electromagnetic wave field.

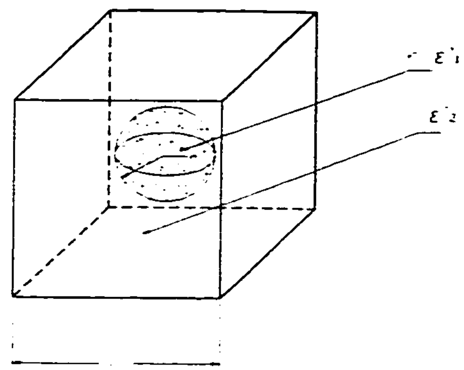

Figure 3.2 Unit element geometry

Yaghjian [1] derived the field decomposition for the calculation of fields in the source region, giving the restriction of the inclusion size for numerical calculation [Figure 3.2]: the maximum chord length d_{max} of a single inclusion is limited by the relation: $d_{max} \approx \frac{\lambda}{2 \cdot \pi}$ where λ is the wave length of the operating field (Table 3.1).

In the mixing theories that result from following analysis only the relative permittivities with the respect to permittivity ε_o will have an effect. Also, inclusion permittivities can be lower than the background dielectric constant as is the case of calculating the effective permittivity of sea ice, for example.

	Designation	Wavelength Range	Frequency Range
elf	Extremely low frequency	10000 to 1000 [km]	30 to 300 [Hz]
vf	Voice frequency	1000 to 100 [km]	300 to 3000 [Hz]
vlf	Very low frequency	100 to 10 [km]	3 to 30 [kHz]
lf	Low frequency	10 to 1[km]	30 to 300 [kHz]
mf	Medium frequency	1000 to 100 [m]	300 to 3000 [kHz]
hf	High frequency	100 to 10 [m]	3 to 30 [MHz]
vhf	Very high frequency	10 to 1 [m]	30 to 300 [MHz]
uhf	Ultra high frequency	100 to 10 [cm]	300 to 3000 [MHz]
shf	Super high frequency	10 to 1 [cm]	3 to 30 [GHz]
ehf	Extremely high frequency	10 to 1 [mm]	30 to 300 [GHz]
-	-	1 to 0.1 [mm]	300 to 3000 [GHz]

Table 3.1 Nomenclature of frequency Bands. Refer to ANSI/IEE std 100-1984

3.4 The Clausius - Mosotti Equation

Taking into account all the mechanisms of polarization in the dielectric material, when the alternating electromagnetic field is applied, total polarization may be expressed as:

$$P = P_e + P_i + P_o \qquad (3.12)$$

Where P_e designates electronic polarization, P_i ionic and P_o is dipole or orientational polarization. Expressing the preceding equation in terms of polarizability, we obtain the following relation:

$$P = N \cdot E' \cdot (\alpha_e + \alpha_i + \alpha_o) \qquad (3.13)$$

Where α_e designates electronic polarizability, α_I ionic polarizability and α_o the dipole or orientational polarizability.

Confronted with three molecular parameters at once (N, α, E'), the tendency in analysis is to eliminate the other two by reasonable approximations. In the present case, the parameter α contains the primary information on the electric charge carriers and their polarizing action, therefore it is more convenient to eliminate the other two parameters, N and E'.

We can assume that the locally acting field, E', will be identical with the externally applied field for gases at low pressure where the interaction between the molecules is neglible. At high pressures, however, and especially at condensed phases of solids and liquids, the field acting on a reference molecule 'A' [Figure 3.3] may be modified decisively by the polarization of the surroundings. To take this effect into account, we assume the following model:[35]

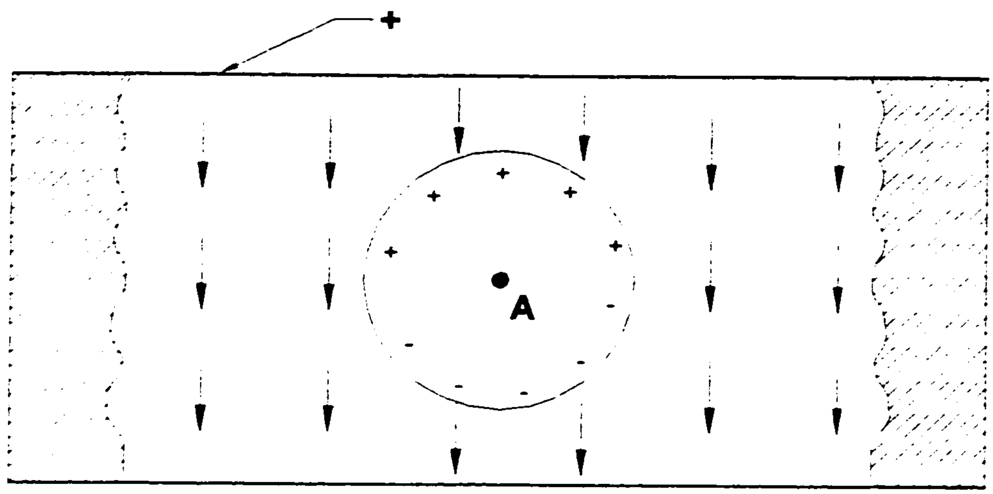

Figure 3.3 Model for calculation of internal field

If the reference molecule "A" is surrounded by an imaginary sphere and beyond the dielectric is treated as a continuum, the following analysis is in order. If the molecules inside this sphere were removed while the polarization outside remains frozen, the field acting on "A" would stem from two sources: the free charges at the electrodes of the plate capacitor E_1 , and the free ends of the dipole chains that line the cavity walls E_2. Actually, there are molecules inside the sphere and they are so near to "A" that their individual positions and shapes have to be considered. This generates an additional contribution, E_3, to the local field E'. Hence we obtain:

$$E' = E_1 + E_2 + E_3 \qquad (3.14)$$

The contribution of the free charges at the electrodes is, by definition, equal to the applied field.

$$E_1 = E \qquad (3.15)$$

To calculate E_2 Lorentz, as discussed in [29, 35] assumed that the charge density lining the cavity walls stems from bound charges, and is correspondingly determined by the normal component of the polarization vector P as shown in Figure 3.4.

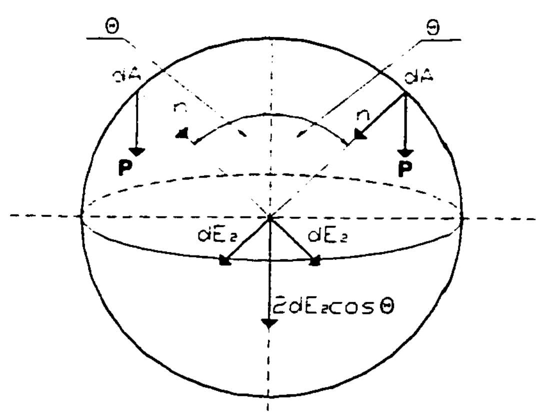

Figure 3.4 Geometry for calculating the E_2 component of the local field

Using Lorentz model and according to Coulomb's law the E_2 component of the local field E' is expressed as:

$$E_2 = \frac{1}{3} \cdot \frac{P}{\varepsilon_0} = \frac{E}{3} \cdot \left(\kappa^{'} - 1\right) \qquad (3.16)$$

Where E is the external field and $\kappa^{'}$ is relative dielectric constant of the material.

An evaluation of the field contribution, E_3, which arises from the individual action of the molecules inside the sphere, [Figure 3.3] requires accurate information on the geometrical arrangement and polarizability of the contributing particles. Even if this information is available, the mathematical treatment is very difficult . In a general way, the existence of these neighboring molecules was already recognized in the calculation of the E_2 local electric field component using Lorentz [29, 35] approach. Based on this assumption the E_3 local electric field component is equal to zero.

$$E_3 = 0 \qquad (3.17)$$

This is a reasonable approximation when the elementary particles are neutral and do not have a permanent dipole moment , or when they are arranged in complete disorder, or in highly symmetrical arrays. This allows us to substitute for the unknown molecular parameter $E^{'}$

$$E^{'} = E_1 + E_2 = E + \frac{P}{3 \cdot \varepsilon_0} = \frac{E}{3} \cdot \left(\kappa^{'} + 2\right) \qquad (3.18)$$

that is , known macroscopic parameters.

By inserting the expression for local field into equation 2.5 we obtain the relationship between the polarizability per unit volume and the relative permittivity of the dielectric, κ': (N is the number of elementary contributing elements per unit volume, and α , their polarizability)

$$\frac{N \cdot \alpha}{3 \cdot \varepsilon_0} = \frac{\kappa' - 1}{\kappa' + 2} \qquad (3.19)$$

Previous equation was first obtained by Clausius and Mossoti. For the composite systems the Clausius-Mosotti relation can be expressed as [22]:

$$\frac{\varepsilon'_{eff} - \varepsilon_0}{\varepsilon'_{eff} + 2 \cdot \varepsilon_0} = \sum_{i=0}^{n} \frac{N_i \cdot \alpha_i}{3 \cdot \varepsilon_0} \qquad (3.20)$$

In the previous equation, n represents the number different types of inclusions (for example solid spheres and hollow spheres in our case, n=2) and ε_0 is background medium permittivity, N_i are the numbers of spherical inclusions per unit volume for each phase, α_i their polarizability and ε'_{eff} is the effective dielectric constant of the composite. Application of previous equation is restricted to the systems where all the types of the inclusions within the mixture are distributed homogeneously.

3.5 Hollow Sphere Composite Model

The composite material investigated in the first phase of this research, consists of hollow ceramic sphere inclusions within an epoxy matrix. This composite system is represented schematically in Figure 3.3.

To determine the effective permittivity of the composite, based on the Clausius- Mossoti relation (equation 3.20), one must calculate the polarizabilties, α_i, for all types of inclusions that compose the mixture. In this case, the polarizability of solid and hollow sphere system. To calculate the polarizability of any symmetrical geometry one must resolve Laplace equation $\nabla^2\Psi = 0$, in spherical coordinates, with the application of proper boundary conditions. To calculate the polarizability for multishell systems in spherical coordinate reference was made to [22 ,28]. Determining the polarizability of the perfect sphere, hollow and solid, can be treated as a problem with axial symmetry and the potential Ψ will be function of θ and r independent of azimuth ϕ (Figure 3.5). The proposed solution [28] for the Laplace equation is of the form:

$$\Psi(r,\Theta)=\sum_{n=0}^{\infty}\left(a_n\cdot r^{-(n+1)}+b_n\cdot r^n\right)\cdot P_n(\cos\Theta) \qquad (3.21)$$

In the previous solution a_n and b_n are constants determined by boundary conditions, and $P_n(\cos\theta)$ is a Legendre polynomial of degree "n".

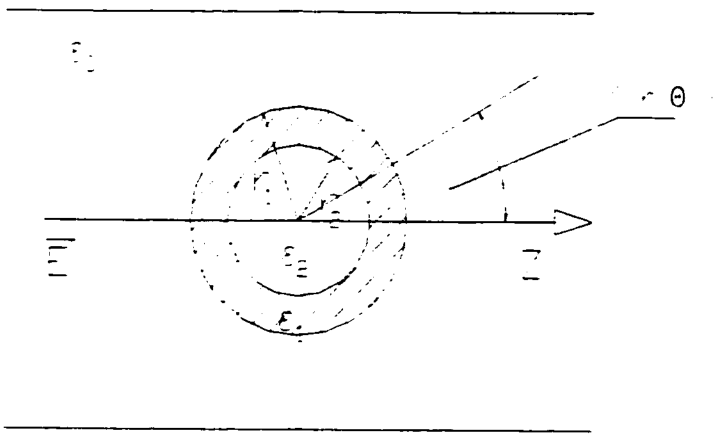

Figure 3.5 Dielectric sphere with spherical shell

The polarizability of a system consisting of an inner sphere with radius r_1, and a dielectric constant, ε_1, surrounded by "n" concentric shells of outer radii r_i and respective dielectric constants ε_i can be expressed as $\alpha^i = f(r_1, r_2, \ldots, r_n, \varepsilon'_1, \varepsilon'_2, \ldots \varepsilon'_n)$. The dielectric sphere of radius r_1 and dielectric constant ε'_1, surrounded by a concentric spherical shell of outer radius r_2 and dielectric constant ε'_2, is of interest for the model consisting of hollow ceramic spheres in a polymer matrix [Figure 3.5]. Upon application of boundary conditions for this system Sihvola [22] obtained the relation for the polarizability of spherical monoshell systems in terms of the system geometry and the dielectric properties of the constituents:

$$\alpha = 4\pi\varepsilon_0 \cdot \frac{(\varepsilon'_1 - \varepsilon_0)\cdot r_1^3 + (2\varepsilon'_1 + \varepsilon_0)\cdot [(\varepsilon'_2 - \varepsilon'_1)\cdot r_2^3 + \rightarrow}{(2\varepsilon'_1 + \varepsilon_0) + 2\cdot(\varepsilon'_1 - \varepsilon_0)\cdot r_1^{-3}\cdot[(\varepsilon'_2 - \varepsilon'_1)\cdot r_2^3 + \rightarrow}$$

$$\frac{\rightarrow + (2\varepsilon'_2 + \varepsilon'_1)/(\varepsilon'_2 + 2\varepsilon_1) + 2(\varepsilon'_2 - \varepsilon'_1)\cdot r_2^3]}{\rightarrow + (2\varepsilon'_2 + \varepsilon'_1)/(\varepsilon'_2 + 2\varepsilon'_1) + 2(\varepsilon'_2 - \varepsilon'_1)\cdot r_2^3]} \qquad (3.22)$$

The polarizability of a solid spherical particle of radius r_1 and a dielectric constant ε'_1, can be obtained from elementary electrostatics [29]. The polarizability of a solid spherical particle, in terms of system geometry and dielectric constant of sphere material, is given by:

$$\alpha = 4\pi\varepsilon_0 r_1^3 \cdot \frac{\varepsilon'_1 - \varepsilon_0}{\varepsilon'_1 + 2\varepsilon_0} \qquad (3.23)$$

By inserting the polarizabilities of hollow and solid spheres into the Clausius - Mossoti relation (equation 3.20), the effective dielectric constant of the composite material can be obtained numerically by solving equation 3.20.

If the dielectric constant for the hollow sphere system is known (by means of direct system measurement, for example), the formula for a composite mixture consisting of two solid spherical inclusions can be used instead. In this case, the composite system which represents the hollow ceramic sphere is treated as a solid spherical inclusion since dielectric constant (and electric losses) are known, and equation 3.23 can be used instead of equation 3.22 which is less computationally involved and thickness (aspect ratio) of the shell need not to be determined, as long as the restriction for the particle size is respected. If the composite mixture consists of two constituents represented by solid spheres, the relation for the effective permittivity of the composite system (3.20) can be expressed in Rayleigh's form [4 , 22]:

$$\frac{\varepsilon'_{eff}-\varepsilon_0}{\varepsilon'_{eff}+2\varepsilon_0}=f_1\frac{\varepsilon'_1-\varepsilon_0}{\varepsilon'_1+2\varepsilon_0}+f_2\frac{\varepsilon'_2-\varepsilon_0}{\varepsilon'_2+2\varepsilon_0} \quad (3.24)$$

In the previous equation, ε'_1, and ε'_2 designate permittivities of the constituents and f_1, and f_2 designate their respective volume fractions within the composite, and it represents the effective medium theory (EMT) based on Clausius-Mossoti relation.

Now it is necessary to define the choice of background medium ε_0. Maxwell - Garnett relations are obtained by setting the background permittivity in equation 3.24 to ε'_1, and ε'_2 respectively, obtaining the bounds for the effective dielectric constant. Robertson W.M. et al. [4] experimentally showed that the Maxwell - Garnett treatment is accurate near the composition extremes where the host constituent dominates over the other. However, away from the extremes neither form is satisfactory. Bruggeman [8] suggested another approach. In his theory the host dielectric, ε_0, is considered to be the effective dielectric permittivity of the mixture, ε'_{eff}, created by constituents ε'_1, and ε'_2. This choice makes the left hand side of equation 3.24 equal to zero. Robertson [4] has shown through experimentation with alumina and zirconia composites, that the Bruggeman theory agrees well over the entire composition range unlike the Maxwell - Garnett equations. Applying the Bruggeman theory , the effective medium theory (3.24) assumes the form:

$$0 = f_1 \frac{\varepsilon'_1 - \varepsilon'_{eff}}{\varepsilon'_1 + 2\varepsilon'_{eff}} + f_2 \frac{\varepsilon'_2 - \varepsilon'_{eff}}{\varepsilon'_2 + 2\varepsilon'_{eff}} \qquad (3.25)$$

This equation applies to the system represented in Figure 3.7. The accuracy of the effective medium theory depends on how well the real microstructure of the sample corresponds to the idealized microscopic model used to derive specific mixture relation.

3.6 Dielectric Constant of Fiber Reinforced Composites

A transversely isotropic fiber reinforced material has two principal dielectric constants: In the fiber directions and normal to the fibers .These are designated as $\varepsilon'_{eff\text{-}a}$ and $\varepsilon'_{eff\text{-}T}$ respectively. For fiber reinforced composite materials the axial effective permittivity follows the rule of the mixture and can be expressed as [17]:

$$\varepsilon'_{eff-a} = \varepsilon'_{1a} \cdot f_1 + \varepsilon'_{2a} \cdot f_2 \qquad (3.26)$$

In the preceding equation, the axial effective permittivity is expressed as a function of the axial dielectric properties of the constituents and their volume fractions within the composite.

Using the composite cylinder assemblage scheme shown in Figure 3.6, [31, 32], Hashin [17], derived the formulation for the effective dielectric constant in the transverse direction. The equation, given in terms of the properties and volume fractions of the constituents, is expressed as:

$$\varepsilon'_{eff-T} = \varepsilon'_1 + \frac{f_2}{\dfrac{1}{\varepsilon'_2 - \varepsilon'_1} + \dfrac{f_1}{2 \cdot \varepsilon'_1}} \qquad (3.27)$$

Where, subscript '2' refers to fiber and '1' is matrix constituent.

To construct the Composite Cylinder Assemblage model (CCA) one might consider a collection of composite cylinders, each consisting of a circular fiber core and a concentric matrix shell. The outer radii of the cylinders may be chosen at will. The fiber core radii are restricted by the requirement that in each cylinder ratio between radii be the same, which also implies that matrix and volume fractions are the same at each composite cylinder. It may be shown [32] that for various constituent loadings each composite cylinder behaves as an equivalent homogeneous cylinder. A hypothetical homogeneous cylindrical specimen is assigned these equivalent properties and is progressively filled out with composite cylinders. The radii of the cylinders can be made arbitrarily small, consequently, the remaining volume can be arbitrarily small also. The construction of the CCA is shown in Figure 3.6.

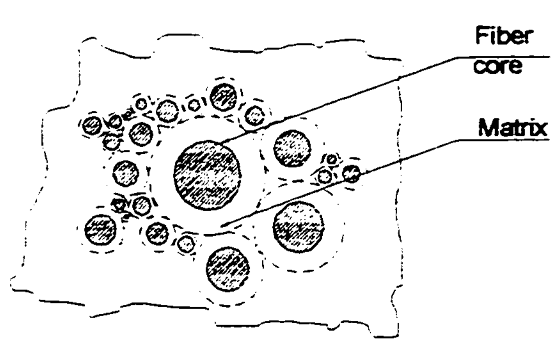

Figure 3.6 Composite Cylinder Assemblage

A desirable feature of the model is the randomness of the fiber placement, whereas an undesirable feature is the large variation of fiber sizes.

Absolute bounds for statistically isotropic, two phase materials are given by Wiener [17] and are derived in [5]. The bounds for the effective permittivity of the two phase composite model are given as:

$$\frac{1}{\frac{f_1}{\varepsilon'_1}+\frac{f_2}{\varepsilon'_2}} \leq \varepsilon'_{eff} \leq f_1 \cdot \varepsilon'_1 + f_2 \cdot \varepsilon'_2 \qquad (3.28)$$

3.7 Treatment of loss tangent

Referring to Figure 3.1 it is evident that to characterize a composite material as a dielectric, one must assess the loss tangent. For most engineering materials, the loss per cycle is a very small fraction of the total stored energy in the dielectric. Refer to Figure

2.6. Using this assumption, Schulgasser and Hashin [18] proposed following model to predict the effective loss tangent of the composite dielectrics consisting of low loss constituents. According to this theory the effective loss factor (ε''_{eff}) can be expressed as a linear combination of the loss factors (ε''_1, ε''_2) of constituents which compose the mixture:

$$\varepsilon''_{eff} = a_1 \cdot \varepsilon''_1 + a_2 \cdot \varepsilon''_2 \qquad (3.29)$$

Bounds on coefficients a_i (i=1,2) in the previous equation can be determined using Prager's equations [33] and are expressed as:

$$\begin{aligned} \frac{1}{f_2}\left(\frac{\varepsilon'_{eff}-\varepsilon'_1}{\varepsilon'_2-\varepsilon'_1}\right)^2 \le a_2 \le \frac{\varepsilon'_{eff}}{\varepsilon'_2} - \frac{\varepsilon'_1}{\varepsilon'_2 \cdot f_1}\left(\frac{\varepsilon'_2-\varepsilon'_{eff}}{\varepsilon'_2-\varepsilon'_1}\right)^2 \\ \frac{1}{f_1}\left(\frac{\varepsilon'_{eff}-\varepsilon'_2}{\varepsilon'_1-\varepsilon'_2}\right)^2 \le a_1 \le \frac{\varepsilon'_{eff}}{\varepsilon'_1} - \frac{\varepsilon'_2}{\varepsilon'_1 \cdot f_2}\left(\frac{\varepsilon'_1-\varepsilon'_{eff}}{\varepsilon'_1-\varepsilon'_2}\right)^2 \end{aligned} \qquad (3.30)$$

Using this approach bounds on effective loss factor (ε''_{eff}) for the two-phase low loss composite can be calculated, if the loss factors of constituents that compose the mixture are known. This can be achieved by means of direct loss factors measurement at particular frequency of interest. In the previous equation ε'_{eff} is the effective dielectric constant of the composite, f_1 and f_2 are volume fractions of the first and second phase in the mixture and ε'_1, ε'_2 the dielectric constants of the constituents that compose the mixture.

Hashin and Schulgasser [18] suggested another set of equations to predict the bounds on the coefficients a_i required in equations 3.29. Their equations are more computationally involved, and they yield the same results as Prager's equations when applied to the composite systems investigated in this thesis work.

The application of this approach depends on the ratio of the constituent losses. For higher ratios, calculated bounds may be wide, impeding their application in further dielectric analysis.

When the effective dielectric constant (ε'_{eff}) and the effective loss factor (ε''_{eff}) of the composite are known the effective loss tangent for the composite system is expressed as:

$$\tan\delta_{eff} = \frac{\varepsilon''_{eff}}{\varepsilon'_{eff}} \qquad (3.31)$$

The proposed equations for prediction of dielectric properties of the composite systems analyzed in this work are given in section 3.8.

3.8 Approach

To fulfill the objectives defined in chapter 2 a three-step approach is taken in this study.

In the first phase of the investigation, a composite material consisting of epoxy matrix and hollow ceramic spheres is manufactured. The hollow ceramic spheres can be considered as a composite system since they are composed of ceramic wall and entrapped air inside the sphere. The effective dielectric constant of the hollow ceramic sphere system is lower than the dielectric constant of the ceramic wall since the relative dielectric constant of the entrapped air is close to unity. Mixing the epoxy with the hollow ceramic spheres will yield the composite system with lower dielectric constant when compared to epoxy. If the increase of the dielectric constant of the epoxy matrix was sought, the solid ceramic inclusions could have been used, since the ceramics have higher dielectric constant than epoxy. In present work, 50 μm diameter hollow ceramic spheres with wall thicknesses of 5-8 μm were used . This composite system, is shown schematically in Figure 3.7:

In Figure 3.7, the solid spheres represent the host epoxy matrix with its initial dielectric constant designated as ε'_3.

In the first phase of analysis the volume fraction of the hollow ceramic spheres in the host epoxy matrix is varied from 0% (epoxy matrix alone) to 80%. This approach enabled us to manufacture a composite system with specific values of the effective dielectric constant within the range of dielectric constants of constituents that compose the mixture. The dielectric data (ε' and tan δ) is experimentally obtained using a dielectric analyzer (DEA) in the 100 Hz to 100 kHz range at room temperature and normal humidity conditions.

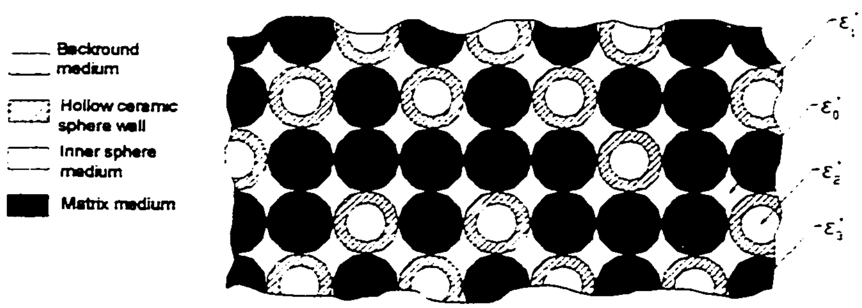

Figure 3.7 Composite Model: Epoxy matrix with hollow ceramic spheres

To predict the effective dielectric constant of the composite system considered in the first phase of investigation, the effective medium theory (EMT) , based on Clausius - Mosotti equation was used [14] . The EMT theory predicts the effective dielectric constant of a composite mixture based on the dielectric properties of the constituents within the mixture. In its final form, the effective dielectric constant of the first composite system, hollow ceramic spheres embedded in an epoxy matrix, can be expressed as :

$$0 = f_1 \frac{\varepsilon'_1 - \varepsilon_{eff}}{\varepsilon'_1 + 2\varepsilon_{eff}} + f_2 \frac{\varepsilon'_2 - \varepsilon_{eff}}{\varepsilon'_2 + 2\varepsilon_{eff}} \qquad (3.32)$$

where the ε'_{eff} designates the effective dielectric constant of the composite material and $\dot{\varepsilon}_1$ and $\dot{\varepsilon}_2$ are the dielectric constants of the hollow ceramic spheres and the matrix respectively. The variables f_1 and f_2 are respective volume fractions in the mixture. The Clausius-Mossoti equation represents the relation between the macroscopic and microscopic dielectric properties of the material.

To completely predict the behavior of the a composite material, a prediction of a loss tangent is required. Based on the theory developed by Hashin and Schulgasser [18] for the low loss dielectrics where the imaginary component was considered small in comparison to the real part, of the complex notation for the dielectric constant. The loss tangent of the composite system can be estimated by the linear combination of the losses of the constituents, and it can be expressed as:

$$\tan \delta_{eff} = \frac{\dot{\varepsilon}_{eff}}{\varepsilon'_{eff}} \qquad (3.33)$$

To determine effective loss factor in previous equation, equations 3.29 to 3.31 were used, and the loss factors of constituents are experimentally determined.

The changes in the density of the composite structure are obtained experimentally for each ceramic hollow sphere volume fraction using the standard ASTM D792-86. The rule of mixture is used to predict the density changes, based on the properties of the constituents. The composite density is predicted as:

$$\rho_c = \rho_s \cdot f_s + \rho_m \cdot f_m \qquad (3.34)$$

In this equation, the composite density is expressed in terms of the densities and the volume fractions of the hollow ceramic inclusions and the matrix.

To compensate for the degradation of the mechanical properties of the epoxy, resulting from the incorporation of hollow ceramic spheres into the matrix, and to reduce the CTE of the composite, fibers are added to the composite structure. Bearing in mind the limited experimental and analytical information on the dielectric behavior of the fiber reinforced polymer matrix composites, dielectric analysis of fiber reinforced epoxy matrix was performed. In the second phase of investigation, E-glass fibers in plain weave form were added to the epoxy matrix at different volume fractions.

The prediction of the dielectric constant for the E-glass/epoxy system was done using the bounds set by Wiener. In their final form these equations can be expressed as:

$$\frac{1}{\frac{f_1}{\varepsilon'_1}+\frac{f_2}{\varepsilon'_2}} \leq \varepsilon'_{eff} \leq f_1 \cdot \varepsilon'_1 + f_2 \cdot \varepsilon'_2 \qquad (3.35)$$

This represents the bounds of the effective dielectric constant of the E-glass/epoxy composite system in terms of its constituents. The loss tangent of this composite was obtained using the same approach taken to predict the effective loss tangent of the epoxy/hollow ceramic spheres system.

The third composite material investigated consisted of an epoxy matrix with 20% - 40% volume fraction of hollow ceramic spheres with E-glass fibers. Dielectric data for this system was collected in the 100 Hz to 100 kHz range at room temperature and normal humidity using the DEA system. The E-glass fibers have the lowest loss tangent among the commercially available fibers. By using E-glass fibers in the plain weave form the quasi-isotropic structure was obtained.

The prediction of the dielectric constant for this multiphase system consisted of using the EMT theory to predict the behavior of the matrix with hollow ceramic spheres in the epoxy and then using the Wiener bounds with these values to predict the effective dielectric constant of the whole multiphase system.

CHAPTER 4

Experimental Procedure and Test Results

4.1 Material Properties

All specimens were fabricated from the following materials:

Liquid epoxy resin DER 324

Supplier:	DOW Chemical corp.
Specific gravity (25^0 C)	1.11 gr/cm^3
Epoxide equivalent Wt.	197-206
Viscosity range (CPS at 25^0 C)	600 - 800
Flexural strength	35.2 kPa
Yield compressive strength	98.2 kPa
Compressive Modulus	2.1 GPa
Tensile Strength	70.96 MPa
Ultimate elongation	6.37 %
Glass transition temperature	102^0 C

Ancamine 2167 Curing Agent

Supplier:	Air Products co.
Epoxide equivalent Wt.	53
Viscosity Range (CPS at 25 ^{0}C)	210
Mixed Viscosity (CPS at 25 ^{0}C)	2340
Gel time (min)	210
Tensile strength	75.79 MPa
Tensile modulus	2.56 GPa
Ultimate elongation	6.9%
Specific Gravity	0.975 gr/cm^3

Hollow ceramic spheres SF 14

Supplier	PQ corp.
Specific Gravity	0.73 gr/cm^3
Particle size (mean)	55 μm
Particle size (range)	10 - 90 μm
Working pressure	10.34 MPa

4.2 Samples Preparation and Testing

The epoxy polymer matrix based on epicchlorohydrin and bisphenol A (DER 324 by D.O.W chemicals) was used as a starting material. Curing agent was cycloaliphatic amine (Ancamine 2167 by Air products). For this system the recommended curing agent to resin ratio was 28 to 100 by weight, and this ratio was used to produce matrix samples. The curing profile for this system was 2 hrs. at 80 °C and 3 hrs at 149 °C.

To determine the density of the cured matrix samples the ASTM specification D792-86 was followed. The density of DER324 epoxy cured with Ancamine 2167 was experimentally obtained, and the average sample density was 1.16 gr/cm^3. Determining the density of the samples as per the D792 standard consists of a specimen weight measurement in air and the fully immersed specimen in the distilled water. The density of the sample can be expressed as a function of the sample weight in air, sample weight when fully immersed in distilled water and the weight of partially immersed attachment (usually wire) that was used to hold sample while the measurements for the fully immersed sample were taken. The density of the sample is given by the following relation:

$$\rho_c = \frac{a}{a+w-b} \cdot 0.9975 \qquad (4.1)$$

where

ρ_c	Density of the composite specimen [gr/cm^3]
a	Weight of the specimen in air [gr]
b	Weight of fully immersed specimen into distilled water [gr]
w	Weight of the partially immersed attachment [gr]

These samples were subjected to dielectric tests in the 100 Hz to 100 kHz range, at room temperature and normal humidity using the dielectric analyzer DEA 2970 in the parallel plate mode. A summary of results is given in Table 4.1.

DER 324	100 Hz	1 kHz	10 kHz	100 kHz
Dielectric Constant	3.32	3.29	3.11	3.20
tan δ	0.0050	0.0083	0.0144	0.0212

Table 4.1 Dielectric properties of DER 324

Hollow ceramic spheres (SF 14 by PQ corp.) were added to DER 324 epoxy matrix at different volume fractions. The average outside diameter of the spheres was 50μm and the thickness of the ceramic wall was estimated to be 5-8μm using the density data. To determine density and dielectric properties of the hollow ceramic spheres special set of samples was produced. These samples consisted of very high volume fraction of hollow spherical inclusion (90%-95%) embedded in epoxy matrix. These samples were used to determine dielectric properties of the hollow ceramic spheres by subjecting them to dielectric tests using DEA 2970 test system. The density data supplied by supplier suggested that the density of the hollow ceramic spheres is 0.7 gr/cm^3, and this value was confirmed experimentally by subjecting samples with high spherical volume fraction to density test as per ASTM specification D792-86. The dielectric data for SF14 hollow ceramic spheres was experimentally obtained in 100 Hz to 100 kHz range at room temperature and normal humidity using DEA 2970 dielectric analyzer. The experimentally obtained data for hollow ceramic spheres is presented in Table 4.2.

SF 14	100 Hz	1 kHz	10 kHz	100 kHz
Dielectric Constant	2.87	2.46	2.16	2.38
tan δ	0.1633	0.0678	0.0240	0.0197

Table 4.2 Dielectric properties of SF 14

The samples containing 10 - 80 % volume fraction of SF14 hollow ceramic spheres were manufactured, by mixing DER 324 epoxy and ancamine 2167 curing agent with SF hollow ceramic spheres. The required weight ratio of the constituents before curing was experimentally obtained in order to obtain desired hollow ceramic spheres volume fraction while preserving suggested weight ratio between curing agent and epoxy. These weight ratios produce samples with 5% accuracy in terms of hollow ceramic spheres volume fractions. The curing profile for this type of composite was 95 °C for 8 hrs and 24 hrs in the air. For each sample included in this study the hollow ceramic spheres volume fraction was verified experimentally using the D792 standard. First, the density of the composite was determined by measuring and applying equation 4.1 and then, based on the densities of the constituents (epoxy and hollow ceramic spheres), which were experimentally obtained the volume fraction of the hollow ceramic inclusions in the epoxy matrix was obtained using the equation:

$$f_f = \frac{\rho_c - \rho_m}{\rho_f - \rho_m} \qquad (4.2)$$

where:

f_f	Fiber (spheres) volume fraction
ρ_m	Density of the matrix [gr/cm^3]
ρ_c	Density of the composite [gr/cm^3]
ρ_f	Fibers (spheres) density [gr/cm^3]

With the volume fraction accurately measured, the samples were subjected to dielectric tests in the 100 Hz to 100 kHz range. Dielectric test results for this composite were compared to the predicted results.

Manufacturing of the samples which consisted of DER 324 epoxy matrix and E-Glass fibers plain weave (J.B. Martin) was done by using the hand lay-up technique. The density of the fiber mat was obtained experimentally using the same approach as for hollow ceramic inclusions, and the density for E-glass fiber mat was determined to be 2.54 [gr/cm^3], based on the samples from three different batches of this material. This was necessary in order to determine the fiber volume fraction of the E-glass/epoxy samples using the equation 4.2. Manufactured samples had a fiber volume fraction of 30% to 40%. Curing profile for these samples was the same as for the DER324 matrix without fibers. The dimension of the E-glass/epoxy samples before dielectric measurement was 25 x 25 mm and 1.5 mm thick. These samples were subjected to dielectric tests at 100 Hz to 100 kHz range at room temperature and normal humidity, using the DEA 2970 dielectric analyzer. Dielectric data for E-glass fibers is presented in Table 4.3.

E-glass	100 Hz	1 kHz	10 kHz	100 kHz
Dielectric Constant	2.51	2.49	2.40	2.50
tan δ	0.0135	0.006	0.0034	0.0045

Table 4.3 Dielectric properties of E-glass (plain weave)

The multiphase composite samples which consisted of DER 324 epoxy matrix , with 20% to 40% hollow ceramic spheres apparent volume fraction and 30 % E-glass fiber plain weave mat were manufactured by using the hand lay up technique. First, the epoxy matrix DER 324 was mixed with SF 14 hollow ceramic spheres to obtain 20% and 40% sphere volume fraction respectively. The E-glass fibers in the plain weave form were wetted with the prepared mixture of epoxy and hollow ceramic inclusions and cured at 90^0 C for 2 hrs and 24 hrs at room temperature. The volume fraction of the E-glass fibers in the SF14/DER324 matrix was obtained experimentally, by following the D792 standard. The density of the SF14/DER324 matrix was estimated using equation 4.1 and this value was used to predict the fiber volume fraction of the whole multiphase mixture .

The samples were cut into the 25 x 25 mm approximately 1.5 mm thick squares, and subjected to dielectric tests in the 100 Hz to 100 kHz at room temperature and normal humidity using the DEA 2970 dielectric analyzer. The structure of the multiphase composite is presented in Figure 4.1. White area represents the E-glass fibers, black area represents hollow ceramic spheres embedded in epoxy matrix.

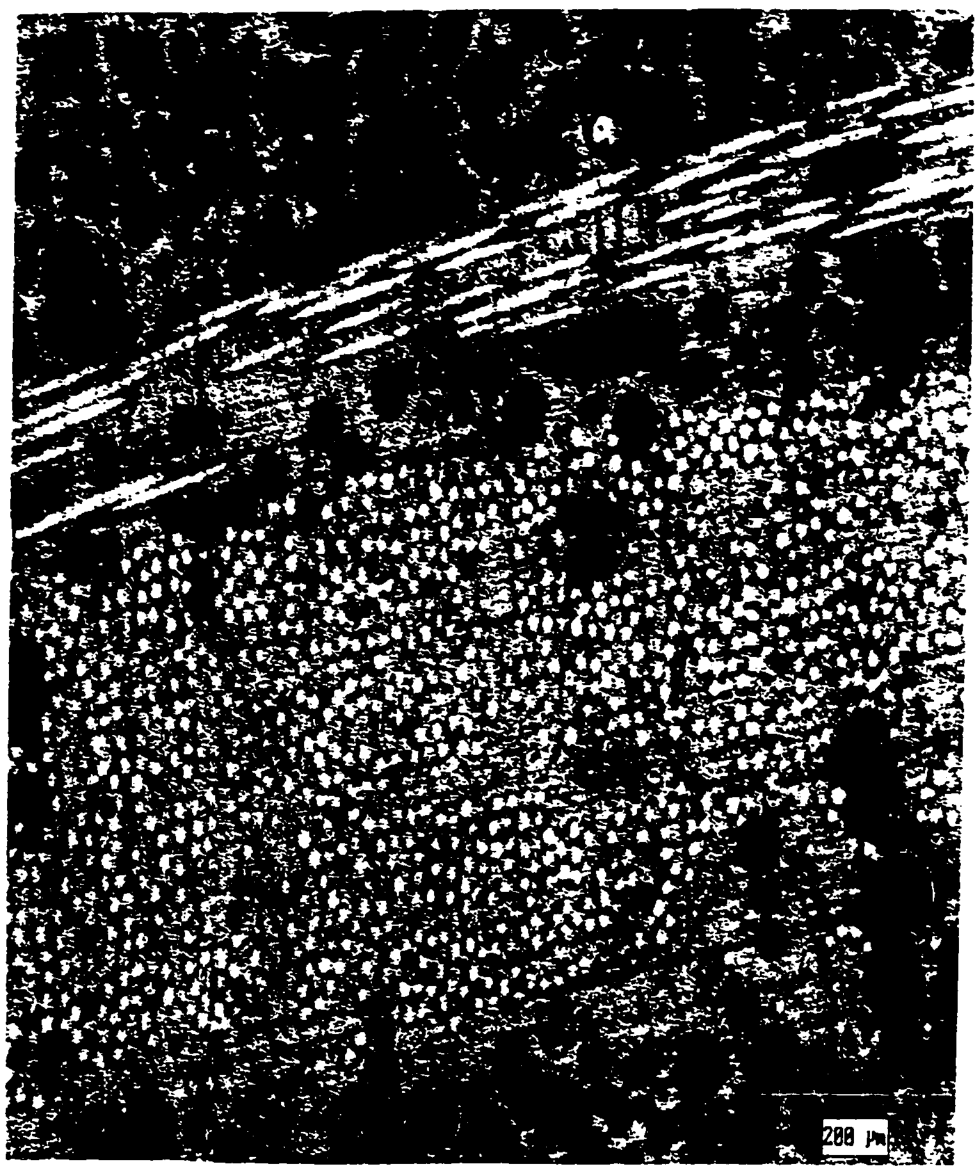

Figure 4.1 Multiphase Composite Structure Micrograph

4.3 Description of DEA 2970 Analysis System

To determine the dielectric properties of a composite material DEA 2970 dielectric system by Du Pont was used. System schematic is presented in Figure 4.2. In the present investigation the parallel plate mode was utilized.

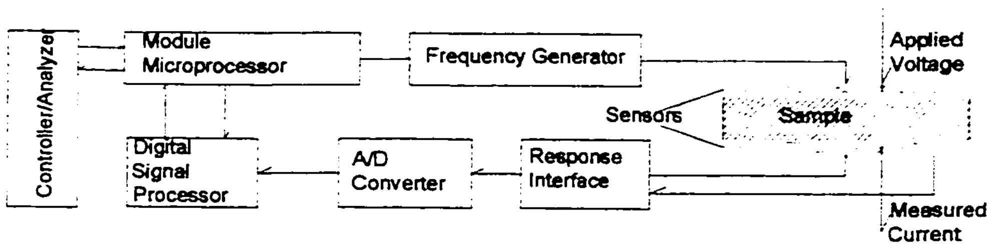

Figure 4.2 Dielectric analyzer DEA 2970 function schematic

Controller/Analyzer is used to program experiments and analyzed data results. Module microprocessor controls all the instrument functions, including operation of the experiment, mathematical manipulation of data and communication with the controller. Frequency generator synthesizes a high purity sine-wave signal to establish an electrical field and to excite the sample. The computer memory stores 32K - point sine wave generation table. Each point is a 16 bit number which gives a signal resolution of 1 part in 64 000. Electrodes (sensors): The input frequency signal at a specified voltage is applied to the sample through the input electrode. The output electrode receives the output current from the sample. A/D converter transforms the amplified signal to the digital format for computer analysis. Digital signal processor: Signals from A/D and information about the applied voltage are used to determine the in phase and out of phase current. The processed phase and gain signals are then sent back to the Module Microprocessor , where they are combined with sample thickness measurements signals to calculate the permittivity (ε') and the loss factor (ε'').

The dielectric characterization of the sample using DEA 2970 involves placing the sample between two golden electrodes and exposing it to an alternating field. The field is created by applying a sinusoidal voltage to one of the electrodes. This produces polarization within the sample, causing oscillation which is at the same frequency as the field but with a phase shift (θ). The phase angle shift is measured by comparing the applied voltage to the measured current [Figure 4.3] .

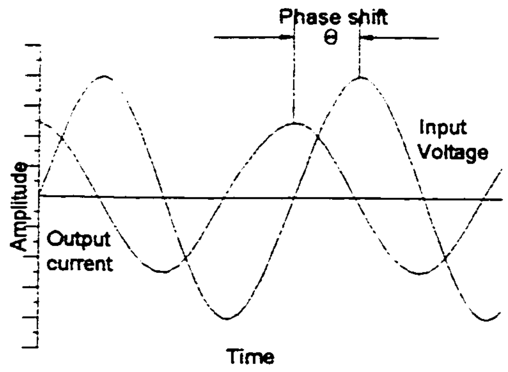

Figure 4.3 Voltage - Current Phase shift

The measured current is separated into capacitance and conductance components [Figure 3.1] . The test equipment calculates these components using following relations:

$$\text{Capacitance} = \frac{I_{\text{MEASURED}}}{V_{\text{APPLIED}}} \cdot \frac{\sin\theta}{2 \cdot \pi \cdot f} \text{ [farads]}$$

$$\text{Conductance} = \frac{I_{\text{MEASURED}}}{V_{\text{APPLIED}}} \cdot \cos\theta \quad \text{[mhos]} \qquad (4.3 \text{ a, b})$$

In previous equations f designates applied field frequency in [Hz] and conductance is 1/R where R is the resistivity in [ohms].

For parallel plate electrodes (sensors) relative dielectric constant ($\kappa^{'}$) and relative loss factor ($\kappa^{''}$) are further obtained using following equations:

$$\kappa^{'} = \frac{c \cdot d}{\varepsilon_0 \cdot A}$$

$$\kappa^{''} = \frac{d}{R \cdot A \cdot 2\pi \cdot f \cdot \varepsilon_0} \qquad (4.4 \text{ a, b})$$

where:

c	Capacitance	[farads]
R	Resistance	[ohm]
A	Electrode plate area	[m^2]
d	Plate spacing	[m]
f	Applied field frequency	[Hz]
ε_0	Absolute permittivity of free space (8.85×10^{-12} [F/m])	

In dielectric analysis experiment , a sample is placed in contact with electrodes and subjected to an applied sinusoidal voltage. Sample response can be measured as a function of the time, temperature and frequency. The electrode assemblies serve two purposes: transmitting the applied voltage to the sample, and sensing the response signals. The parallel plate sensor [Figure 4.4] uses two gold plated electrodes to evaluate bulk dielectric properties in a material and to track molecular relaxation. The lower electrode positioned at the bottom of the furnace [Figure 4.5] applies the voltage and sets up the alternating electric field to polarize the sample. The Upper electrode, attached to the face of the ram, [Figure 4.5], measures the generated current, which is then converted to an output voltage current and amplified. A guard ring around the perimeter of the upper electrode prevents electric field fringing and stray capacitance at the edge of the plates. The electrodes are screen printed gold on ceramic substrates. A platinum resistance temperature detector (RTD) around the circumference of the bottom electrode continuously measures the sample temperature. Signal circuits are connected through pads on the lower sensor which are contacted by spring loaded probes attached to the ram. Accuracy and reproducibility are assured because plate spacing and force on the sample are continuously measured and controlled during the experiment. This corrects for sample expansion/contraction and maintains the good electrode/sample-surface contact.

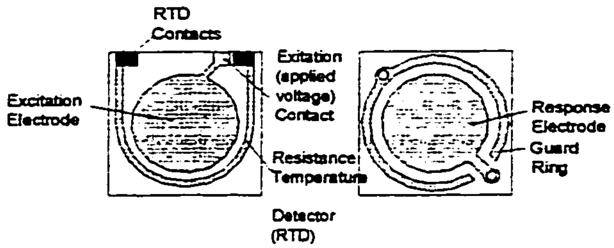

Figure 4.4 Ceramic Sensors

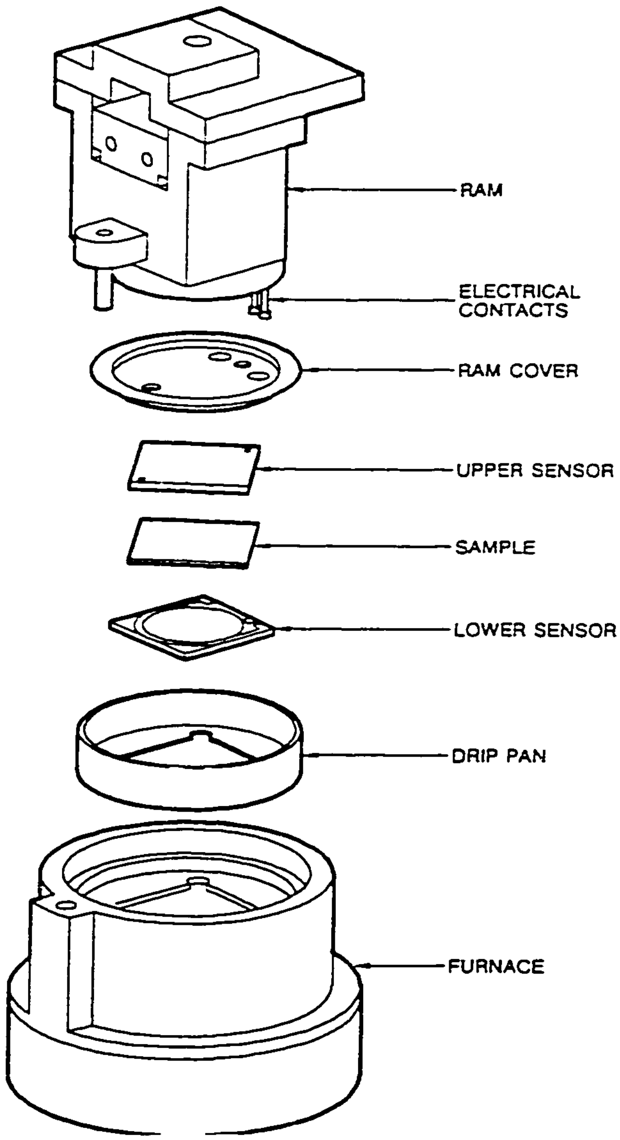

Figure 4.5 DEA 2970 Furnace Assembly

4.4 Test Results

Experimentally obtained dielectric data and theoretical predictions based on recommended dielectric models are presented in the following.

4.4.1 Epoxy Matrix with Hollow Ceramic Spheres

Testing and manufacturing of the samples were performed in three phases. The first phase of the testing consisted of manufacturing the Epoxy matrix samples with hollow ceramic inclusions. To predict the dielectric constant of the Epoxy/ceramic system investigated in this phase of the research the equation for effective permittivity based on Clausius- Mossoti theory [4] is used, and it is expressed as:

$$0 = f_1 \frac{\varepsilon'_1 - \varepsilon'_{eff}}{\varepsilon'_1 + 2\varepsilon'_{eff}} + f_2 \frac{\varepsilon'_2 - \varepsilon'_{eff}}{\varepsilon'_2 + 2\varepsilon'_{eff}} \qquad (4.5)$$

The prediction of the effective permittivity (ε_{eff}) , based on the previous equation requires the values of the dielectric constants (ε'_1 , ε'_2) of the constituents that compose the composite system, and their respective volume fractions in the mixture (f_1, f_2), which were obtained experimentally. The experimental dielectric data were obtained in the 100 Hz to 100 kHz range using the DEA 2970 dielectric analyzer.

The prediction of the loss tangent for the Epoxy/ceramic system was done using the Hashin-Schulgasser theory [18], expressed by the linear combination of the loss tangents of constituents in the mixture and is given as:

$$\tan\delta_{eff} = \frac{1}{\varepsilon_{eff}}(a_1 \cdot \tan\delta_1 + a_2 \cdot \tan\delta_2) \qquad (4.6)$$

Where coefficients a_1 and a_2 are obtained by the Prager's equations (3.30), and the loss tangents ($\tan\ \delta_1$ and $\tan\ \delta_2$) are obtained experimentally, by the loss tangent measurement of the composite system constituents in the 100 Hz to 100kHz range using DEA 2970 dielectric Analyzer. Prager equations require estimate of the effective permittivity, to obtain coefficients a_1 and a_2 which was initially done, using Clausius-Mosssoti relation expressed by equation (4.5).

The combination of the equations (4.5) and (4.6) enabled the theoretical prediction of effective permittivity and loss tangent of the epoxy/ceramic composite system in the 100 Hz to 100 kHz range, for the 0%-80% volume fraction of ceramic spherical inclusions investigated in this phase of research.

The theoretical data (computer output) is presented for each frequency of investigation, and the results for effective permittivity, loss tangent derivatives and loss tangent are presented in table format. The experimental (measured) dielectric data are presented in Figures 4.6 to 4.13, Tables 4.4 to 4.12 and compared to predicted values. In the theoretical prediction (computer output) following notation is used:

Vs	Volume fraction of hollow ceramic spheres in the mixture (f_2)
Vm	Matrix volume fraction (f_1)
Low D_i	Lower Prager coefficients (a_1)
High D_i	High Prager coefficients (a_2)
E_{eff}	Effective permittivity of the composite system (ε'_{eff})
Tan delta bounds	Effective loss tangent bounds (tan δ_{eff})

Comparing the experimentally obtained results with predicted values, the following can be concluded for the DER324/SF 14 system investigated at this phase of research: Effective medium theory based on Clausius-Mossoti theory (equation 4.5) can accurately predict effective dielectric constant of this composite system throughout all the frequency range of investigation (Figures 4.6, 4.8, 4.10, 4.12). Dielectric constant of epoxy matrix is reduced by introduction of hollow ceramic spheres into the matrix.

Effective loss tangent increases with the increase of the hollow spheres volume fraction in the epoxy matrix. Model used to predict effective loss tangent (equations 3.25, 3.29 to 3.31) yielded close bounds, and the obtained data scatter was larger than bounds predicted. However, the experimental data follows the trend predicted by this model (Figures 4.7, 4.9, 4.11, 4.13).

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Permittivity Analysis:
2Phase: DER324 & SF14 at 100Khz
Fiber type: Spherical inclusions
Reference temperature: 28 [C]

Ematrix: 3.200000
Efiber: 2.380000

No:	Vs:	Vm:	Eeff:
0	0.000000	1.000000	3.200000
1	0.050000	0.950000	3.155342
2	0.100000	0.900000	3.111031
3	0.150000	0.850000	3.067074
4	0.200000	0.800000	3.023477
5	0.250000	0.750000	2.980247
6	0.300000	0.700000	2.937389
7	0.350000	0.650000	2.894912
8	0.400000	0.600000	2.852820
9	0.450000	0.550000	2.811120
10	0.500000	0.500000	2.769819
11	0.550000	0.450000	2.728923
12	0.600000	0.400000	2.688437
13	0.650000	0.350000	2.648367
14	0.700000	0.300000	2.608720
15	0.750000	0.250000	2.569500
16	0.800000	0.200000	2.530714
17	0.850000	0.150000	2.492366
18	0.900000	0.100000	2.454461
19	0.950000	0.050000	2.417004
20	1.000000	0.000000	2.380000

Loss Tangent Analysis - DERIVATIVES:
2Phase: DER324 & SF14 at 100Khz
Fiber type: Spherical inclusions
Reference temperature: 28 [C]

No:	Vs:	Low D1:	High D1	Low D2	High D2
1	0.050000	0.941099	0.941926	0.059320	0.060430
2	0.100000	0.883084	0.884644	0.117719	0.119817
3	0.150000	0.825963	0.828166	0.175186	0.178148
4	0.200000	0.769748	0.772502	0.231710	0.235414
5	0.250000	0.714448	0.717664	0.287279	0.291602
6	0.300000	0.660072	0.663660	0.341882	0.346705
7	0.350000	0.606630	0.610500	0.395509	0.400712
8	0.400000	0.554131	0.558195	0.448149	0.453614
9	0.450000	0.502581	0.506754	0.499794	0.505403

Table 4.4 Estimate of dielectric properties for DER324/SF14 composite system (to be continued)

10	0.500000	0.451990	0.456184	0.550433	0.556072
11	0.550000	0.402363	0.406494	0.600059	0.605614
12	0.600000	0.353707	0.357692	0.648664	0.654022
13	0.650000	0.306029	0.309786	0.696240	0.701291
14	0.700000	0.259333	0.262781	0.742781	0.747417
15	0.750000	0.213625	0.216685	0.788281	0.792395
16	0.800000	0.168907	0.171503	0.832734	0.836223
17	0.850000	0.125184	0.127239	0.876135	0.878898
18	0.900000	0.082457	0.083898	0.918482	0.920419
19	0.950000	0.040729	0.041484	0.959771	0.960786
20	1.000000	0.000000	0.000000	1.000000	1.000000

Frequency: 100000.000000 [Hz]
Fiber type: Spherical inclusions
Reference temperature: 28 [C]

Matrix loss: 0.021200
Sphere loss: 0.019700

No:	Vs:	Vm:	Tan delta Bounds		Ave loss
1	0.050000	0.950000	0.021115	0.021149	0.021132
2	0.100000	0.900000	0.021031	0.021097	0.021064
3	0.150000	0.850000	0.020947	0.021041	0.020994
4	0.200000	0.800000	0.020865	0.020984	0.020924
5	0.250000	0.750000	0.020783	0.020924	0.020853
6	0.300000	0.700000	0.020702	0.020861	0.020782
7	0.350000	0.650000	0.020622	0.020797	0.020709
8	0.400000	0.600000	0.020543	0.020729	0.020636
9	0.450000	0.550000	0.020465	0.020659	0.020562
10	0.500000	0.500000	0.020388	0.020586	0.020487
11	0.550000	0.450000	0.020312	0.020510	0.020411
12	0.600000	0.400000	0.020238	0.020432	0.020335
13	0.650000	0.350000	0.020165	0.020351	0.020258
14	0.700000	0.300000	0.020094	0.020267	0.020180
15	0.750000	0.250000	0.020024	0.020180	0.020102
16	0.800000	0.200000	0.019956	0.020090	0.020023
17	0.850000	0.150000	0.019889	0.019997	0.019943
18	0.900000	0.100000	0.019824	0.019901	0.019863
19	0.950000	0.050000	0.019761	0.019802	0.019782
20	1.000000	0.000000	0.019700	0.019700	0.019700

End of Analysis for 2Phase: DER324 & SF14 at 100Khz

Table 4.4 Estimate of dielectric properties for DER324/SF14 composite system

Composite:	**DER 324, with SF14**
Curing Process:	7 hr at 90 C, 24 hr at room temperature
Test System:	DEA 2970 du PONT
Temperature:	28 C
Humidity:	50% RH
Frequency:	**100 kHz**

Dielectric Constant

Spheres Volume fraction	Model [-]	sample 1	sample 2	sample 3	sample 4	sample5
0%	3.20	3.15	3.18	3.39	3.20	3.20
10%	3.11	3.12				
15%	3.07	2.86	2.85			
20%	3.02	2.89	2.94			
25%	2.98	3.08				
30%	2.94	3.06	3.03	2.95	2.77	
40%	2.85	2.68				
45%	2.81	2.63				
50%	2.77	2.69				
55%	2.73	2.68	2.59	2.88		
75%	2.57	2.49	2.50	2.50		
80%	2.53	2.51				
100%	2.38	2.48	2.53	2.32	2.35	2.23

Table 4.5 Dielectric Constant of DER324/SF14 composite at 100 kHz

Composite:	**DER 324, with SF14**
Curing Process:	7 hr at 90 C, 24 hr at room temperature
Test System:	DEA 2970 du PONT
Temperature:	28 C
Humidity:	50% RH
Frequency:	**100 kHz**

Loss Tangent

Spheres Volume Fraction	Low	High	sample 1	sample2	sample3	sample 4	sample5
0%	0.0212		0.0228	0.0213	0.0210	0.0195	0.0215
10%	0.0210	0.0212	0.0204				
15%	0.0209	0.0210	0.0195	0.0197			
20%	0.0209	0.0210	0.0191	0.0194			
25%	0.0208	0.0209	0.0184				
30%	0.0207	0.0209	0.0189	0.0185	0.0183	0.0189	
40%	0.0205	0.0207	0.0222				
45%	0.0205	0.0207	0.0228				
50%	0.0204	0.0206	0.0209				
55%	0.0203	0.0205	0.0211	0.0218	0.0198		
75%	0.0200	0.0202	0.0194	0.0194	0.0196		
80%	0.0200	0.0201	0.0205				
100%	0.0194		0.0211	0.0199	0.0188	0.0200	0.0187

Table 4.6 Loss Tangent of DER324/SF14 composite at 100 kHz

DER324 with SF14 at 100 kHz

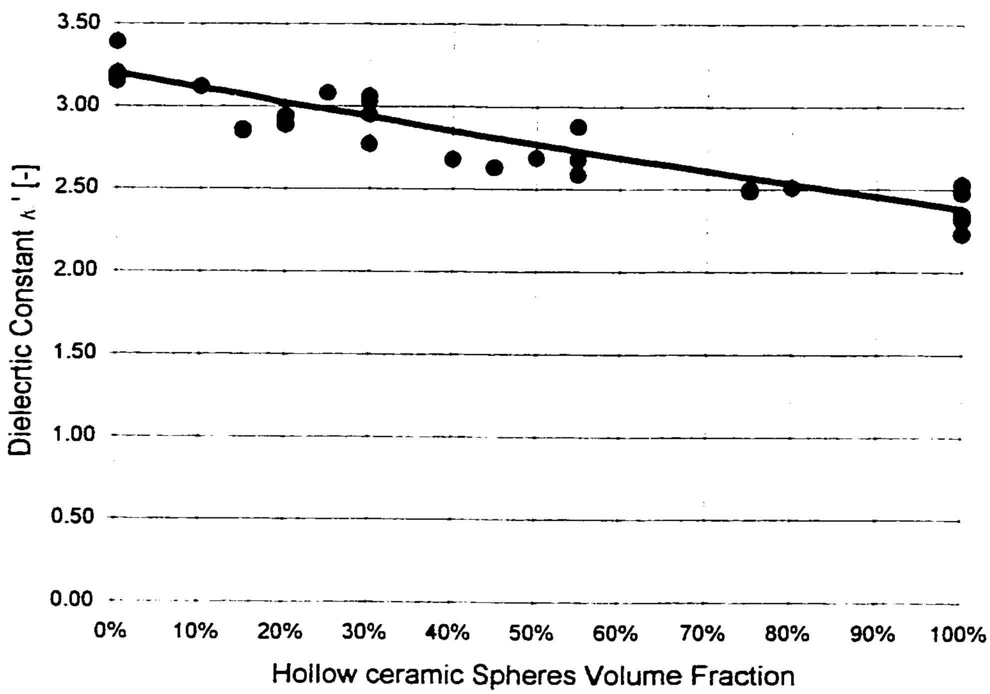

Figure 4.6 Dielectric Constant of DER324/SF14 at 100 kHz
(Solid line - Prediction, Dots - Experiment)

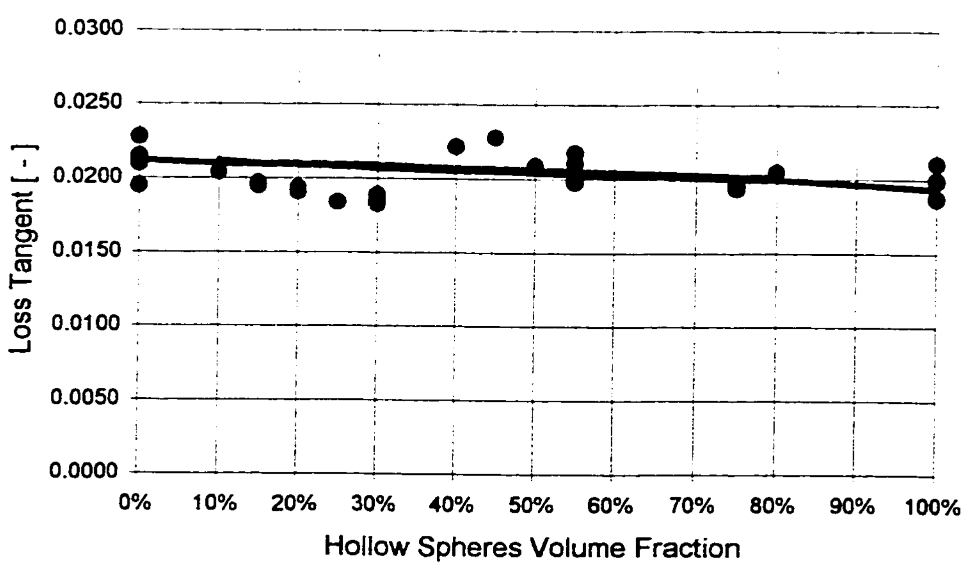

Figure 4.7 Loss Tangent of DER324/SF14 at 100 kHz
(Solid line - Prediction, Dots - Experiment)

Composite:	**DER 324, with SF14**
Curing Process:	7 hr at 90 C, 24 hr at room temperature
Test System:	DEA 2970 du PONT
Temperature:	28 C
Humidity:	50% RH
Frequency:	**10 kHz**

Dielectric Constant

Spheres Volume fraction	Model [-]	sample 1	sample 2	sample 3	sample 4	sample5
0%	3.11	3.05	3.11	3.29	3.09	3.03
10%	3.00	3.07				
15%	2.95	2.80	2.80			
20%	2.90	2.98	2.84	2.89		
25%	2.85	2.92				
30%	2.80	2.75	2.91	2.94	2.86	2.69
40%	2.70	2.64				
45%	2.65	2.51				
50%	2.60	2.45				
55%	2.56	2.54	2.49	2.71		
75%	2.38	2.39	2.40	2.39		
80%	2.33	2.43				
100%	2.16	2.12	2.28	2.16	2.20	2.03

Table 4.7 Dielectric Constant of DER324/SF14 composite at 10 kHz

Composite:	**DER 324, with SF14**
Curing Process:	7 hr at 90 C, 24 hr at room temperature
Test System:	DEA 2970 du PONT
Temperature:	28 C
Humidity:	50% RH
Frequency:	**10 kHz**

Loss Tangent

Spheres Volume Fraction	Low	High	sample 1	sample2	sample3	sample 4	sample5
0%	0.0144		0.0148	0.0146	0.0146	0.0135	0.0147
10%	0.0152	0.0153	0.0156				
15%	0.0156	0.0158	0.0157	0.0151			
20%	0.0160	0.0162	0.0148	0.0152			
25%	0.0165	0.0167	0.0169				
30%	0.0169	0.0171	0.0179	0.0171	0.0171	0.0180	0.0162
40%	0.0178	0.0181	0.0206				
45%	0.0183	0.0186	0.0211				
50%	0.0187	0.0191	0.0223				
55%	0.0193	0.0195	0.0210	0.0190	0.0217		
75%	0.0213	0.0215	0.0251	0.0263	0.0231		
80%	0.0218	0.0220	0.0268				
100%	0.0240		0.0246	0.0245	0.0240	0.0237	0.0252

Table 4.8 Loss Tangent of DER324/SF14 composite at 10 kHz

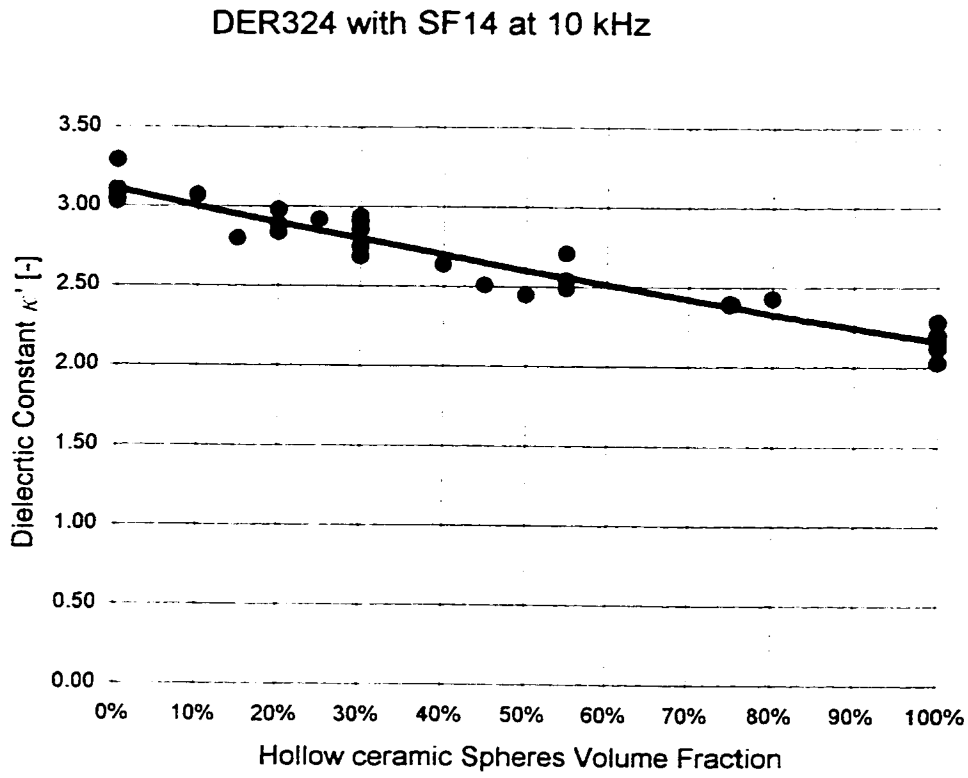

Figure 4.8 Dielectric Constant of DER324/SF14 at 10 kHz
(Solid line - Prediction, Dots - Experiment)

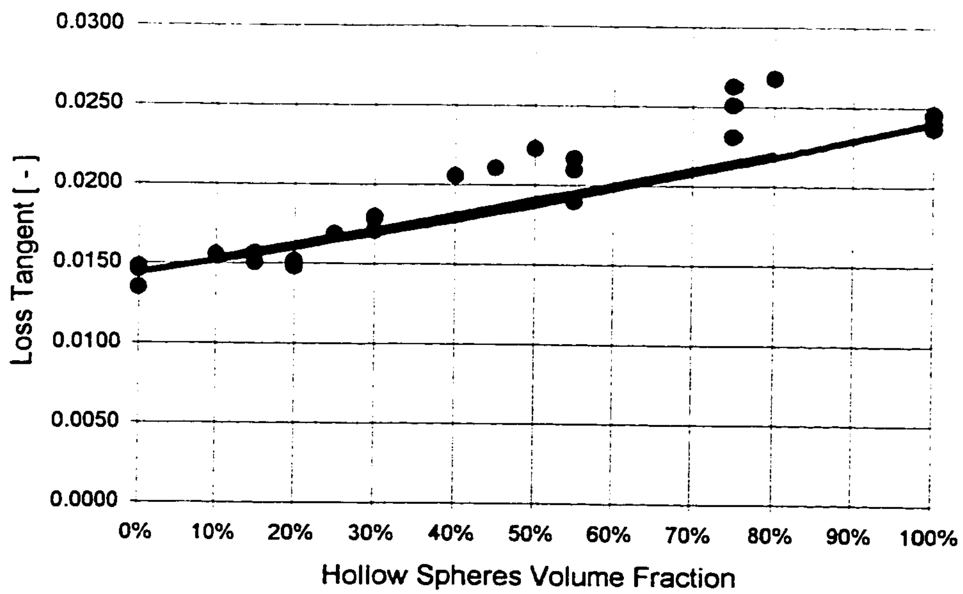

Figure 4.9 Loss Tangent of DER324/SF14 at 10 kHz
(Solid line - Prediction, Dots - Experiment)

Composite:	**DER 324, with SF14**
Curing Process:	7 hr at 90 C, 24 hr at room temperature
Test System:	DEA 2970 du PONT
Temperature:	28 C
Humidity:	50% RH
Frequency:	**1 kHz**

Dielectric Constant

Spheres Volume fraction	Model [-]	sample 1	sample 2	sample 3	sample 4	sample5
0%	3.29	3.27	3.18	3.23	3.27	3.48
10%	3.20	3.22				
15%	3.15	2.94	2.94			
20%	3.11	2.98	3.05			
25%	3.07	3.16				
30%	3.02	3.00	3.14	3.14	3.06	2.83
40%	2.94	2.78				
45%	2.90	2.72				
50%	2.86	2.70				
55%	2.81	2.84	2.73	2.71		
75%	2.65	2.67	2.66	2.67		
80%	2.61	2.71				
100%	2.46	2.41	2.61	2.46	2.52	2.30

Table 4.9 Dielectric Constant of DER324/SF14 composite at 1 kHz

Composite:	**DER 324, with SF14**
Curing Process:	7 hr at 90 C, 24 hr at room temperature
Test System:	DEA 2970 du PONT
Temperature:	28 C
Humidity:	50% RH
Frequency:	**1 kHz**

Loss Tangent

Spheres Volume Fraction	Low	High	sample 1	sample2	sample3	sample 4	sample5
0%	0.0083		0.0076	0.0085	0.0086	0.0085	0.0085
10%	0.0137	0.0138	0.0156				
15%	0.0163	0.0165	0.0157	0.0161			
20%	0.0192	0.0194	0.0150	0.0155			
25%	0.0219	0.0222	0.0276				
30%	0.0248	0.0251	0.0215	0.0257	0.0245	0.0222	0.0249
40%	0.0305	0.0309	0.0342				
45%	0.0335	0.0338	0.0460				
50%	0.0364	0.0368	0.0421				
55%	0.0394	0.0399	0.0411	0.0379	0.0342		
75%	0.0517	0.0520	0.0643	0.0609	0.0633		
80%	0.0549	0.0551	0.0652				
100%	0.0678		0.0685	0.0681	0.0671	0.0662	0.0714

Table 4.10 Loss Tangent of DER324/SF14 composite at 1 kHz

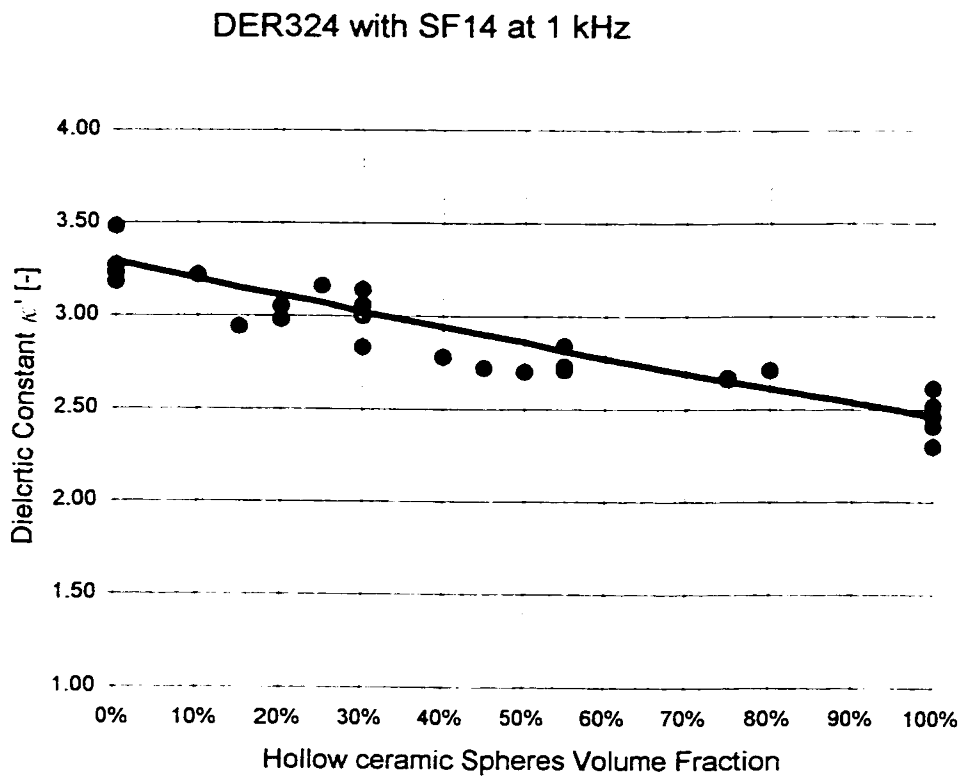

Figure 4.10 Dielectric Constant of DER324/SF14 at 1 kHz
(Solid line - Prediction, Dots - Experiment)

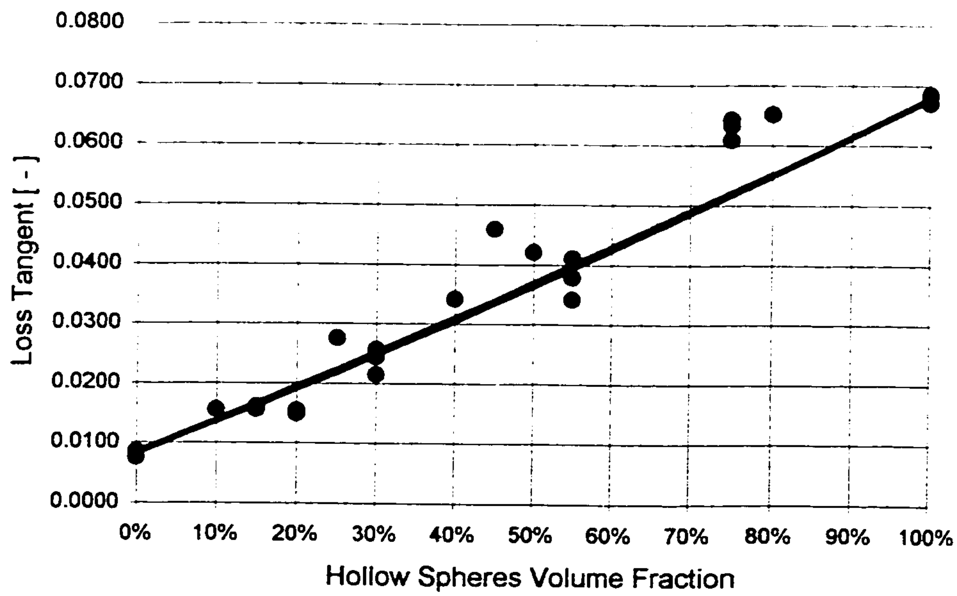

Figure 4.11 Loss Tangent of DER324/SF14 at 1 kHz
(Solid line - Prediction, Dots - Experiment)

Composite:	**DER 324, with SF14**
Curing Process:	7 hr at 90 C, 24 hr at room temperature
Test System:	DEA 2970 du PONT
Temperature:	28 C
Humidity:	50% RH
Frequency:	**100 Hz**

Dielectric Constant

Spheres Volume fraction	Model [-]	sample 1	sample 2	sample 3	sample 4	sample5
0%	3.32	3.26	3.30	3.52	3.30	3.22
10%	3.27	3.31				
15%	3.25	3.03	3.03			
20%	3.22	3.05	3.11			
25%	3.20	3.34				
30%	3.18	3.20	3.33	3.25	2.99	3.33
40%	3.13	2.99				
45%	3.11	2.90				
50%	3.09	2.81				
55%	3.07	3.24	3.03	3.23		
75%	2.97	3.13	3.11	3.13		
80%	2.96	3.20				
100%	2.87	2.80	3.04	2.86	2.93	2.69

Table 4.11 Dielectric Constant of DER324/SF14 composite at 100 Hz

Composite:	**DER 324, with SF14**
Curing Process:	7 hr at 90 C, 24 hr at room temperature
Test System:	DEA 2970 du PONT
Temperature:	28 C
Humidity:	50% RH
Frequency:	**100 Hz**

Loss Tangent

Spheres Volume Fraction	Low	High	sample 1	sample2	sample3	sample 4	sample5
0%	0.0050		0.0048	0.0057	0.0049	0.0047	0.0050
10%	0.0201	0.0202	0.0207				
15%	0.0277	0.0278	0.0237	0.0236			
20%	0.0353	0.0354	0.0271	0.0268			
25%	0.0430	0.0431	0.0569	0.0569			
30%	0.0507	0.0509	0.0545	0.0578	0.0539	0.0604	0.0535
40%	0.0664	0.0666	0.0680				
45%	0.0742	0.0744	0.0895				
50%	0.0821	0.0823	0.1050				
55%	0.0900	0.0902	0.0974	0.0980	0.0956		
75%	0.1222	0.1223	0.1355	0.1438	0.1441		
80%	0.1303	0.1304	0.1423				
100%	0.1633		0.1587	0.1671	0.1608	0.1648	0.1651

Table 4.12 Loss Tangent of DER324/SF14 composite at 100 Hz

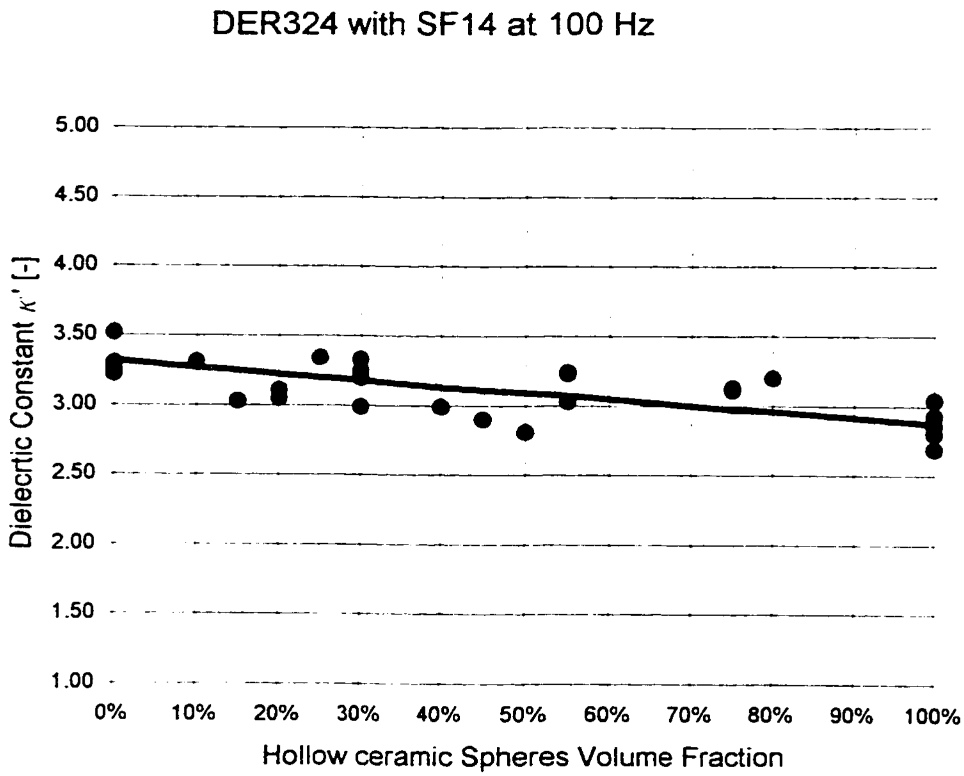

Figure 4.12 Dielectric Constant of DER324/SF14 at 100 Hz
(Solid line - Prediction, Dots - Experiment)

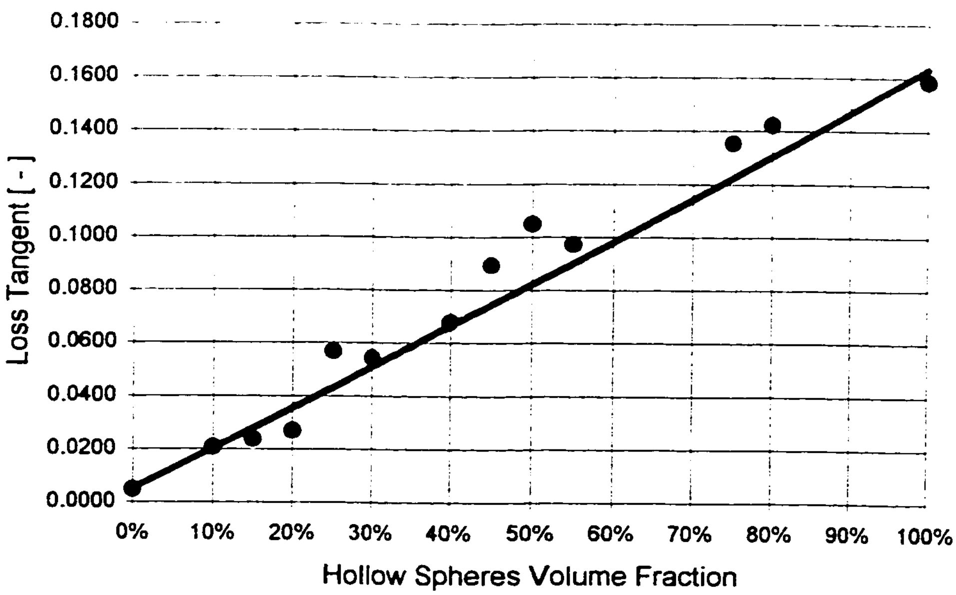

Figure 4.13 Loss Tangent of DER324/SF14 at 100 Hz
(Solid line - Prediction, Dots - Experiment)

4.4.2 Epoxy Matrix with E-glass Fibers

In the second phase of the research the dielectric behavior of epoxy/ E-glass fibers composite system was investigated. To predict the dielectric constant of the system equations proposed by Wiener [17] are used. These equations are given as:

$$\frac{1}{\frac{f_1}{\varepsilon'_1}+\frac{f_2}{\varepsilon'_2}} \leq \varepsilon'_{eff} \leq f_1 \cdot \varepsilon'_1 + f_2 \cdot \varepsilon'_2 \qquad (4.7)$$

To apply previous equations the dielectric constants and volume fractions of the constituents that compose the mixture are required and are obtained experimentally in the 100 Hz -100 kHz range using the DEA 2970 dielectric analyzer. These equations yielded theoretical bounds on the effective permittivity of the composite system.

To determine the effective loss tangent of the epoxy/E-glass system, investigated in this phase, the combination of the equations (3.29 to 3.31) was used, like in the epoxy/ceramic system loss tangent estimate. The upper bound for the effective permittivity of the equation (4.7) was used to estimate Prager's coefficients required by the equation (3.30).

Theoretical and measured results for effective dielectric constant and effective loss tangent for the epoxy/E-glass system, investigated in this stage of the investigation, are presented in graph and table format. In the theoretical dielectric analysis (computer output) for the epoxy/E-glass system the following notation is used:

Vs	Volume fraction of hollow ceramic spheres in the mixture (f_2)
Vm	Matrix volume fraction (f_1)
Low D_i	Lower Prager coefficients (a_1)
High D_i	High Prager coefficients (a_2)
Elow	Effective permittivity of the composite system (low bound) (ε'_{eff})
Elhigh	Effective permittivity of the composite system (high bound) (ε'_{eff})
Tan delta bounds	Effective loss tangent bounds (tan δ_{eff})

The effective dielectric constant of the Epoxy/E-glass system, investigated in this phase of research was predicted using equation 3.27. Better correlation between predicted values and measured data is obtained at lower fiber volume fraction of E-glass fibers and at higher frequencies (Figures 4.14, 4.16, 4.18 and 4.20).

Effective loss tangent prediction for the Epoxy/E-glass system was based in the equation 4.6. Model predictions are higher then values obtained by direct effective loss tangent measurement (Figures 4.15, 4.17, 4.19, 4.21). This tendency is observed for all frequencies investigated in the present work.

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Permittivity Analysis:
Eglass/Epoxy (plain weave mat) at 100 Khz
Fiber type: Continuous fibers
Reference temperature: 28 [C]

Ematrix: 3.200000
Efiber: 2.500000

No:	Vs:	Vm:	Elow:	Ehigh:	Eave:
0	0.000000	1.000000	3.200000	3.200000	3.200000
1	0.050000	0.950000	3.155819	3.165000	3.160409
2	0.100000	0.900000	3.112840	3.130000	3.121420
3	0.150000	0.850000	3.071017	3.095000	3.083009
4	0.200000	0.800000	3.030303	3.060000	3.045152
5	0.250000	0.750000	2.990654	3.025000	3.007827
6	0.300000	0.700000	2.952030	2.990000	2.971015
7	0.350000	0.650000	2.914390	2.955000	2.934695
8	0.400000	0.600000	2.877698	2.920000	2.898849
9	0.450000	0.550000	2.841918	2.885000	2.863459
10	0.500000	0.500000	2.807018	2.850000	2.828509
11	0.550000	0.450000	2.772964	2.815000	2.793982
12	0.600000	0.400000	2.739726	2.780000	2.759863
13	0.650000	0.350000	2.707276	2.745000	2.726138
14	0.700000	0.300000	2.675585	2.710000	2.692793
15	0.750000	0.250000	2.644628	2.675000	2.659814
16	0.800000	0.200000	2.614379	2.640000	2.627190
17	0.850000	0.150000	2.584814	2.605000	2.594907
18	0.900000	0.100000	2.555911	2.570000	2.562955
19	0.950000	0.050000	2.527646	2.535000	2.531323
20	1.000000	0.000000	2.500000	2.500000	2.500000

Loss Tangent Analysis - DERIVATIVES:
Eglass/Epoxy (plain weave mat) at 100 Khz
Fiber type: Continous fibers
Loss analysis based on AVE BOUNDS for Effective perimittivity
Reference temperature: 28 [C]

No:	Vs:	Low D1:	High D1	Low D2	High D2
1	0.050000	0.936929	0.937646	0.063977	0.064895
2	0.100000	0.875653	0.876994	0.126016	0.127732
3	0.150000	0.816084	0.817958	0.186217	0.188616
4	0.200000	0.758138	0.760458	0.244674	0.247644
5	0.250000	0.701737	0.704420	0.301473	0.304907
6	0.300000	0.646807	0.649774	0.356696	0.360493
7	0.350000	0.593280	0.596453	0.410419	0.414480
8	0.400000	0.541090	0.544395	0.462714	0.466944
9	0.450000	0.490176	0.493542	0.513650	0.517958

Table 4.13 Estimate of dielectric properties for DER324/E-glass composite system
(to be continued)

10	0.500000	0.440482	0.443840	0.563289	0.567587
11	0.550000	0.391951	0.395236	0.611691	0.615895
12	0.600000	0.344535	0.347681	0.658913	0.662941
13	0.650000	0.298183	0.301130	0.705009	0.708781
14	0.700000	0.252850	0.255539	0.750027	0.753469
15	0.750000	0.208494	0.210867	0.794016	0.797053
16	0.800000	0.165073	0.167075	0.837020	0.839582
17	0.850000	0.122549	0.124126	0.879081	0.881100
18	0.900000	0.080885	0.081986	0.920240	0.921649
19	0.950000	0.040046	0.040621	0.960535	0.961270
20	1.000000	0.000000	0.000000	1.000000	1.000000

Frequency: 100000.000000 [Hz]
Fiber type: Continous fibers
Reference temperature: 28 [C]

Matrix loss: 0.021200
Sphere loss: 0.004500

No:	Vs:	Vm:	Tan delta Bounds		Ave loss
1	0.050000	0.950000	0.020339	0.020358	0.020349
2	0.100000	0.900000	0.019485	0.019521	0.019503
3	0.150000	0.850000	0.018637	0.018687	0.018662
4	0.200000	0.800000	0.017794	0.017856	0.017825
5	0.250000	0.750000	0.016955	0.017028	0.016992
6	0.300000	0.700000	0.016120	0.016202	0.016161
7	0.350000	0.650000	0.015288	0.015377	0.015332
8	0.400000	0.600000	0.014459	0.014552	0.014505
9	0.450000	0.550000	0.013631	0.013728	0.013679
10	0.500000	0.500000	0.012805	0.012903	0.012854
11	0.550000	0.450000	0.011980	0.012077	0.012028
12	0.600000	0.400000	0.011155	0.011249	0.011202
13	0.650000	0.350000	0.010330	0.010419	0.010374
14	0.700000	0.300000	0.009504	0.009586	0.009545
15	0.750000	0.250000	0.008676	0.008750	0.008713
16	0.800000	0.200000	0.007847	0.007909	0.007878
17	0.850000	0.150000	0.007015	0.007065	0.007040
18	0.900000	0.100000	0.006180	0.006216	0.006198
19	0.950000	0.050000	0.005342	0.005361	0.005352
20	1.000000	0.000000	0.004500	0.004500	0.004500

End of Analysis for Eglass/Epoxy (plain weave mat) at 100 Khz

Table 4.13 Estimate of dielectric properties for DER324/E-glass composite system

Composite:	**DER 324 with E-glass fibers (plain weave mat)**
Curing process:	2hrs at 80 C and 3 hrs 149 C (ancamine 2167 curing agent)
Test system	DEA 2970 du Pont
Temperature	28 C
Humidity	50% RH
Frequency	**100 kHz**

Dielectric Constant

Fiber volume fraction	Model Low	High	Data sample1	sample2	sample3	sample4
30%	2.95	2.99	2.84	3.03	2.89	3.14
35%	2.91	2.96	2.78	2.81		
40%	2.88	2.92	2.71	2.75		

Table 4.14 Dielectric Constant of DER324/E-glass at 100 kHz

Loss Tangent

Fiber volume fraction	Model Low	High	Data sample1	sample2	sample3	sample4
30%	0.0161	0.0162	0.0132	0.0143	0.0133	0.0149
35%	0.0153	0.0154	0.0113	0.0126		
40%	0.0145	0.0146	0.0112	0.0117		

Table 4.15 Loss Tangent of DER324/E-glass at 100 kHz

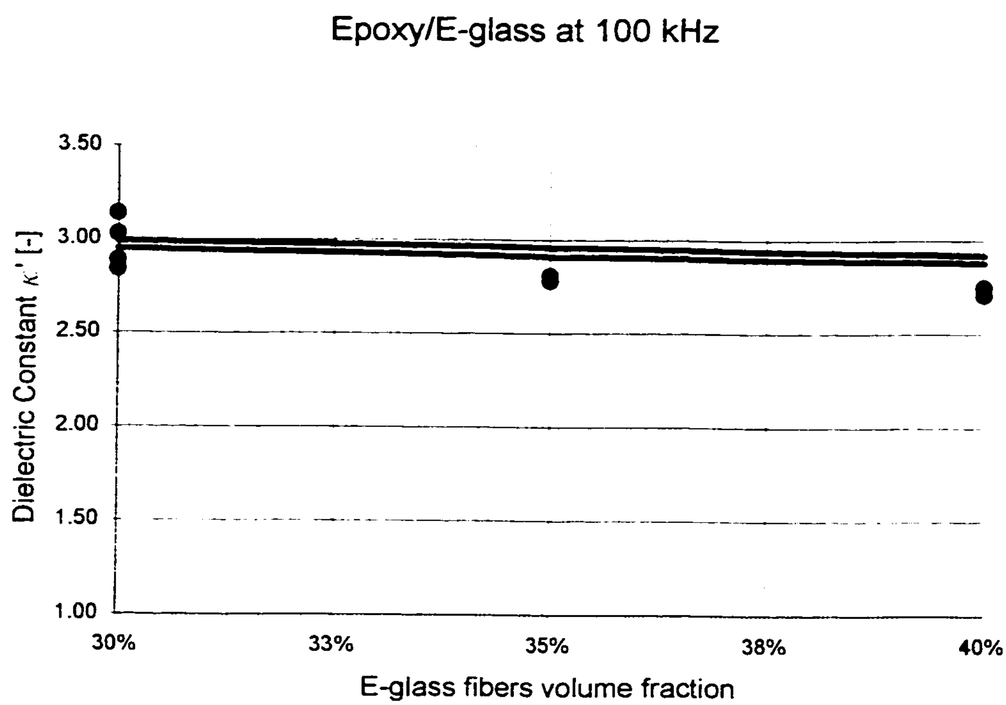

Figure 4.14 Dielectric Constant of DER324/E-glass system at 100 kHz
(Solid line - Prediction, Dots - Experiment)

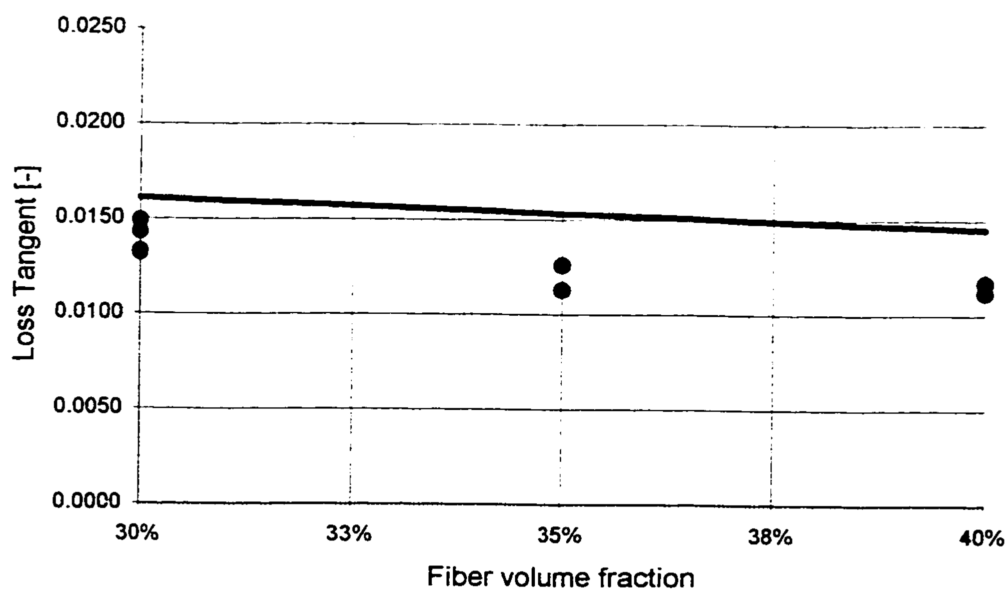

Figure 4.15 Loss Tangent of DER324/E-glass system at 100 kHz
(Solid line - Prediction, Dots - Experiment)

Composite:	**DER 324 with E-glass fibers (plain weave mat)**
Curing process:	2hrs at 80 C and 3 hrs 149 C (ancamine 2167 curing agent)
Test system	DEA 2970 du Pont
Temperature	28 C
Humidity	50% RH
Frequency	**10 kHz**

Dielectric Constant

Fiber volume fraction	Model Low	High	Data sample1	sample2	sample3	sample4
30%	2.86	2.9	2.71	2.9	2.71	2.91
35%	2.82	2.86	2.73	2.81		
40%	2.78	2.83	2.69	2.64		

Table 4.16 Dielectric Constant of DER324/E-glass at 10 kHz

Loss Tangent

Fiber volume fraction	Model Low	High	Data sample1	sample2	sample3	sample4
30%	0.0110	0.0111	0.0089	0.0092	0.0086	0.0088
35%	0.0105	0.0106	0.0072	0.0091		
40%	0.0096	0.0100	0.0077	0.0083		

Table 4.17 Loss Tangent of DER324/E-glass at 10 kHz

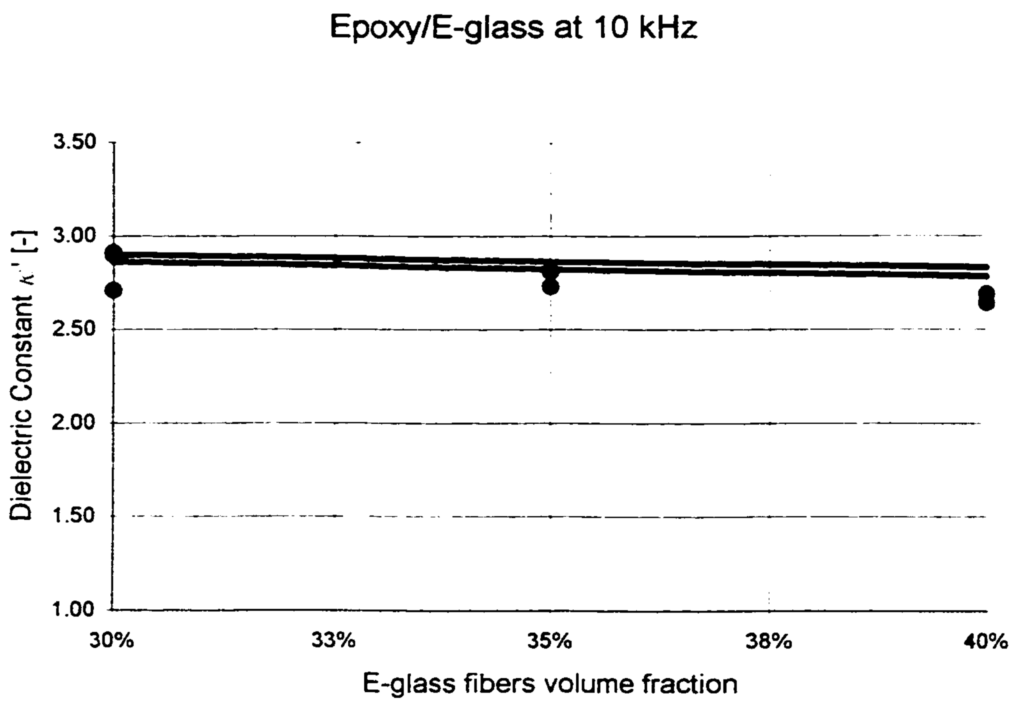

Figure 4.16 Dielectric Constant of DER324/E-glass system at 10 kHz
(Solid line - Prediction, Dots - Experiment)

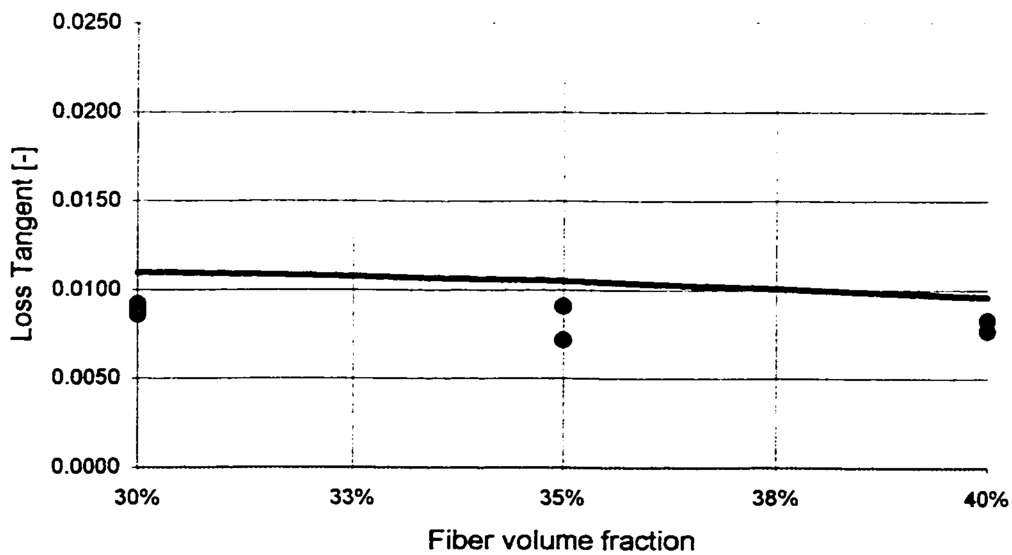

Figure 4.17 Loss Tangent of DER324/E-glass system at 10 kHz
(Solid line - Prediction, Dots - Experiment)

Composite:	**DER 324 with E-glass fibers (plain weave mat)**
Curing process:	2hrs at 80 C and 3 hrs 149 C (ancamine 2167 curing agent)
Test system	DEA 2970 du Pont
Temperature	28 C
Humidity	50% RH
Frequency	**1 kHz**

Dielectric Constant

Fiber volume fraction	Model Low	High	Data sample1	sample2	sample3	sample4
30%	3.00	3.05	2.86	3.05	2.89	3.13
35%	2.96	3.01	2.77	2.86		
40%	2.92	2.97	2.71	2.75		

Table 4.18 Dielectric Constant of DER324/E-glass at 1 kHz

Loss Tangent

Fiber volume fraction	Model Low	High	Data sample1	sample2	sample3	sample4
30%	0.0076	0.0076	0.0061	0.0061	0.0600	0.0760
35%	0.0075	0.0075	0.0063	0.0067		
40%	0.0073	0.0074	0.0063	0.0068		

Table 4.19 Loss Tangent of DER324/E-glass at 1 kHz

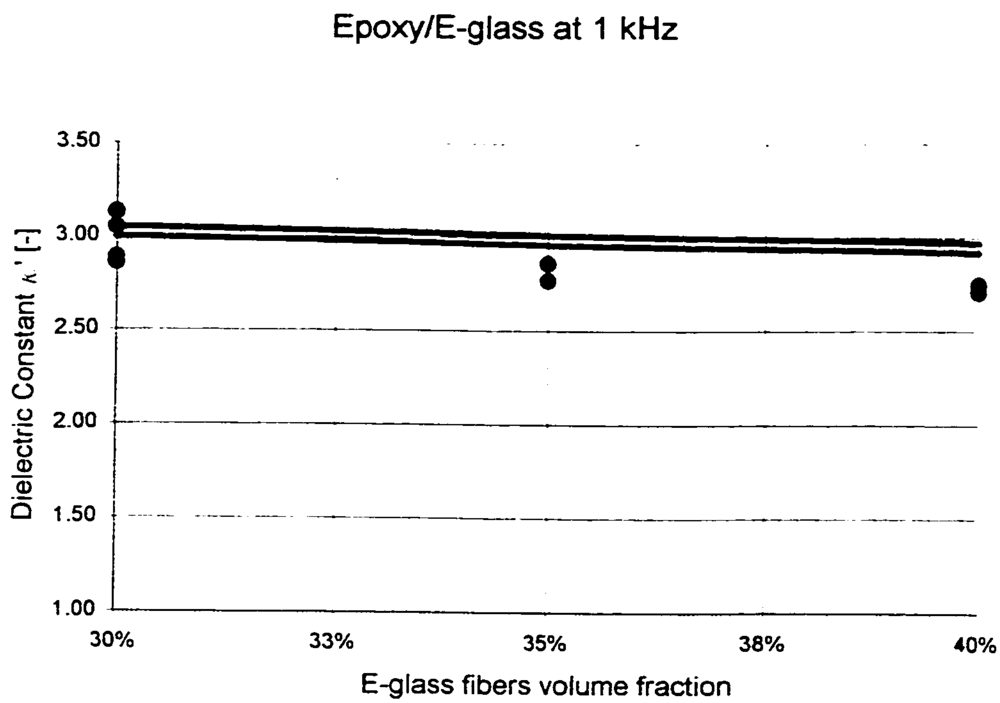

Figure 4.18 Dielectric Constant of DER324/E-glass system at 1 kHz
(Solid line - Prediction, Dots - Experiment)

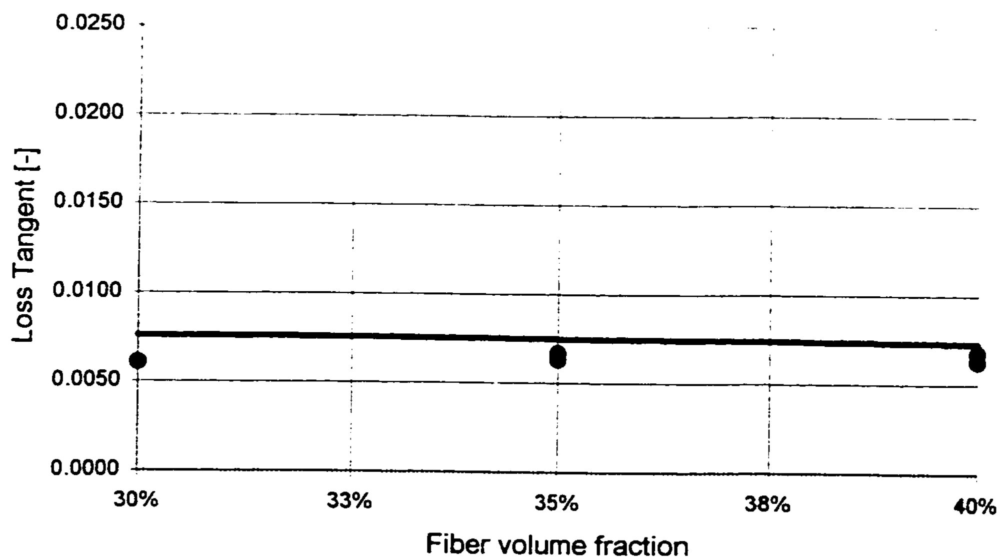

Figure 4.19 Loss Tangent of DER324/E-glass system at 1 kHz
(Solid line - Prediction, Dots - Experiment)

Composite:	**DER 324 with E-glass fibers (plain weave mat)**
Curing process:	2hrs at 80 C and 3 hrs 149 C (ancamine 2167 curing agent)
Test system	DEA 2970 du Pont
Temperature	28 C
Humidity	50% RH
Frequency	**100 Hz**

Dielectric Constant

Fiber volume fraction	Model Low	High	Data sample1	sample2	sample3	sample4
30%	3.03	3.08	2.88	3.08	2.93	3.16
35%	2.98	3.07	2.79	2.84		
40%	2.94	2.97	2.74	2.78		

Table 4.20 Dielectric Constant of DER324/E-glass at 100 Hz

Loss Tangent

Fiber volume fraction	Model Low	High	Data sample1	sample2	sample3	sample4
30%	0.0075	0.0076	0.0055	0.0058	0.0084	0.0057
35%	0.0079	0.0080	0.0063	0.0067		
40%	0.0084	0.0085	0.0070	0.0068		

Table 4.21 Loss Tangent of DER324/E-glass at 100 Hz

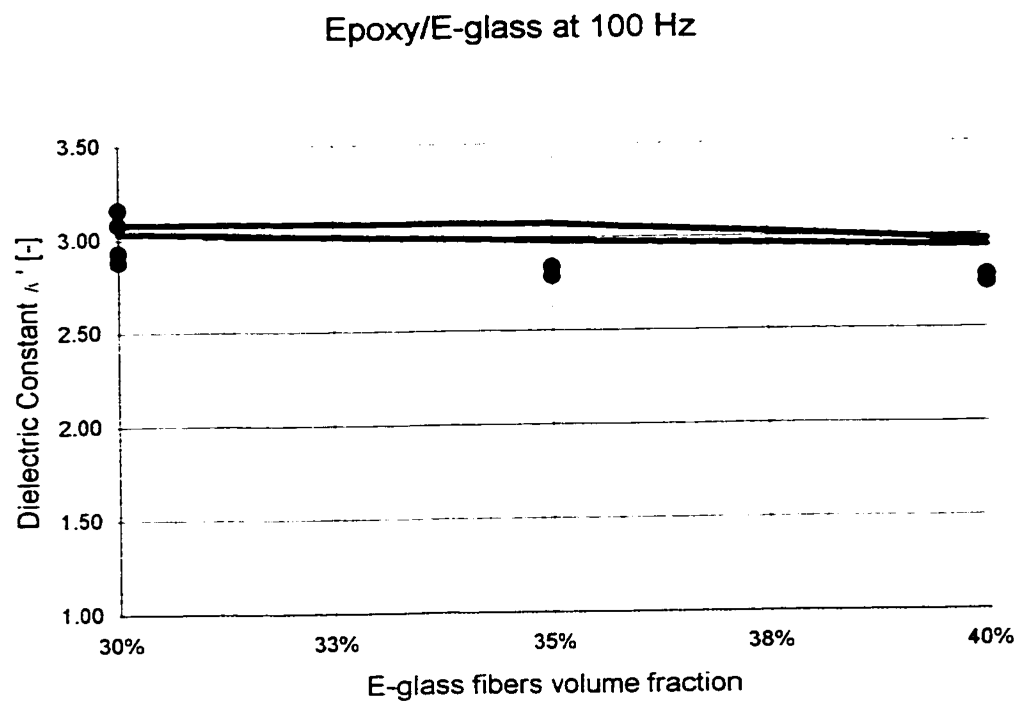

Figure 4.20 Dielectric Constant of DER324/E-glass system at 100 Hz
(Solid line - Prediction, Dots - Experiment)

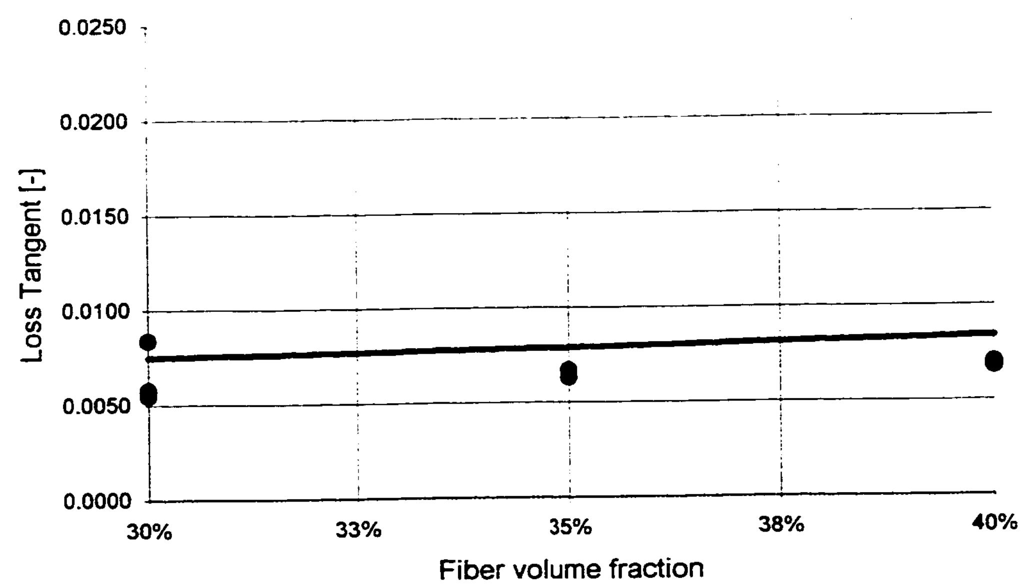

Figure 4.21 Loss Tangent of DER324/E-glass system at 100 Hz
(Solid line - Prediction, Dots - Experiment)

4.4.3 Multiphase Composite System (Epoxy/Ceramic -E-glass)

To predict the Effective dielectric constant of the multiphase composite system the 'two step model' approach was used. First, the effective dielectric constant of the Epoxy/Ceramic system was predicted using equation (3.25) which is the similar approach to that one taken in the first phase of the research. Effective permittivity values obtained by this theory were used as the input for the Wiener equations (3.28) to obtain the bounds for the effective permittivity of the 3-phase composite system which consists of hollow ceramic spheres and E-glass fibers embedded in the epoxy matrix.

To determine the effective loss tangent of the multiphase composite system, investigated in this phase, the combination of the equations (3.25, 3.28 to 3.31) was used, like in the epoxy/ceramic system loss tangent estimate. The upper bound for the effective permittivity of the equation (3.28) was used to estimate Prager's coefficients required by equation (3.30).

Theoretical and measured results for effective dielectric constant and effective loss tangent for the multiphase composite system, investigated in this stage of the investigation are presented in graph and table format. In the theoretical dielectric analysis (computer output) for the epoxy/E-glass system the following notation is used:

Vs	Volume fraction of hollow ceramic spheres in the mixture (f_2)
Vm	Matrix volume fraction (f_1)

Low D_i	Lower Prager coefficients (a_1)
High D_i	High Prager coefficients (a_2)
Elow	Effective permittivity of the composite system (low bound) (ε'_{eff})
Elhigh	Effective permittivity of the composite system (high bound) (ε'_{eff})
Tan delta bounds	Effective loss tangent bounds (tan δ_{eff})

Modeling, of dielectric properties, of multiphase composite system investigated in this study is based on the equations 3.25, 3.28 to 3.31. Better correlation between experimental data and predicted dielectric values is observed at higher frequencies (Figures 4.22 to 4.25). At higher volume fraction of hollow-ceramic spheres (40%) in the Epoxy/E-glass mixture and at low frequencies (100 Hz to 1 kHz), effective loss tangent prediction is lower than measured values (Figure 4.25). This can be considered as a limitation of this model.

File run ID: Sun Nov 08 14:50:19 1998

Permittivity Analysis:
Matrix: 20%SF14 and 80% Epoxy FIBERS: E-glass plain weave mat at 100kHz
Fiber type: Continous fibers
Reference temperature: 28 [C]

Ematrix: 3.020000
Efiber: 2.500000

No:	Vs:	Vm:	Elow:	Ehigh:	Eave:
0	0.000000	1.000000	3.020000	3.020000	3.020000
1	0.050000	0.950000	2.988915	2.994000	2.991458
2	0.100000	0.900000	2.958464	2.968000	2.963232
3	0.150000	0.850000	2.928627	2.942000	2.935313
4	0.200000	0.800000	2.899386	2.916000	2.907693
5	0.250000	0.750000	2.870722	2.890000	2.880361
6	0.300000	0.700000	2.842620	2.864000	2.853310
7	0.350000	0.650000	2.815063	2.838000	2.826532
8	0.400000	0.600000	2.788035	2.812000	2.800018
9	0.450000	0.550000	2.761522	2.786000	2.773761
10	0.500000	0.500000	2.735507	2.760000	2.747754
11	0.550000	0.450000	2.709978	2.734000	2.721989
12	0.600000	0.400000	2.684922	2.708000	2.696461
13	0.650000	0.350000	2.660324	2.682000	2.671162
14	0.700000	0.300000	2.636173	2.656000	2.646087
15	0.750000	0.250000	2.612457	2.630000	2.621228
16	0.800000	0.200000	2.589163	2.604000	2.596582
17	0.850000	0.150000	2.566281	2.578000	2.572141
18	0.900000	0.100000	2.543801	2.552000	2.547900
19	0.950000	0.050000	2.521710	2.526000	2.523855
20	1.000000	0.000000	2.500000	2.500000	2.500000

Loss Tangent Analysis - DERIVATIVES:
Matrix: 20%SF14 and 80% Epoxy FIBERS: E-glass plain weave mat at 100kHz
Fiber type: Continous fibers
Reference temperature: 28 [C]

No:	Vs:	Low D1:	High D1	Low D2	High D2
1	0.050000	0.940247	0.940668	0.060256	0.060765
2	0.100000	0.881755	0.882544	0.119179	0.120133
3	0.150000	0.824477	0.825584	0.176820	0.178157
4	0.200000	0.768368	0.769744	0.233227	0.234888
5	0.250000	0.713386	0.714982	0.288447	0.290374
6	0.300000	0.659489	0.661259	0.342523	0.344661
7	0.350000	0.606639	0.608538	0.395499	0.397792
8	0.400000	0.554799	0.556783	0.447413	0.449810
9	0.450000	0.503933	0.505960	0.498305	0.500753

Table 4.22 Estimate of dielectric properties for 3phase composite system
(to be continued)

10	0.500000	0.454008	0.456035	0.548211	0.550660
11	0.550000	0.404990	0.406979	0.597165	0.599567
12	0.600000	0.356850	0.358760	0.645202	0.647510
13	0.650000	0.309557	0.311351	0.692353	0.694520
14	0.700000	0.263083	0.264724	0.738648	0.740630
15	0.750000	0.217401	0.218853	0.784116	0.785871
16	0.800000	0.172485	0.173714	0.828787	0.830270
17	0.850000	0.128311	0.129281	0.872685	0.873857
18	0.900000	0.084853	0.085532	0.915837	0.916657
19	0.950000	0.042090	0.042446	0.958268	0.958697
20	1.000000	0.000000	0.000000	1.000000	1.000000

Frequency: 100000.000000 [Hz]
Fiber type: Continous fibers
Reference temperature: 28 [C]

Matrix loss: 0.020900
Sphere loss: 0.005000

No:	Vs:	Vm:	Tan delta Bounds		Ave loss
1	0.050000	0.950000	0.020090	0.020101	0.020096
2	0.100000	0.900000	0.019284	0.019305	0.019295
3	0.150000	0.850000	0.018482	0.018511	0.018496
4	0.200000	0.800000	0.017682	0.017719	0.017700
5	0.250000	0.750000	0.016884	0.016928	0.016906
6	0.300000	0.700000	0.016089	0.016138	0.016113
7	0.350000	0.650000	0.015296	0.015348	0.015322
8	0.400000	0.600000	0.014504	0.014559	0.014531
9	0.450000	0.550000	0.013713	0.013770	0.013741
10	0.500000	0.500000	0.012923	0.012981	0.012952
11	0.550000	0.450000	0.012133	0.012190	0.012162
12	0.600000	0.400000	0.011344	0.011399	0.011372
13	0.650000	0.350000	0.010555	0.010607	0.010581
14	0.700000	0.300000	0.009765	0.009813	0.009789
15	0.750000	0.250000	0.008974	0.009018	0.008996
16	0.800000	0.200000	0.008183	0.008220	0.008201
17	0.850000	0.150000	0.007390	0.007419	0.007404
18	0.900000	0.100000	0.006595	0.006616	0.006606
19	0.950000	0.050000	0.005799	0.005810	0.005804
20	1.000000	0.000000	0.005000	0.005000	0.005000

End of Analysis for Matrix: 20%SF14 and 80% Epoxy FIBERS: E-glass plain weave mat at 100kHz

Table 4.22 Estimate of dielectric properties for 3phase composite system

Composite:	**DER 324 with 20% SF14 and 30% E-glass fibers**
Curing process:	7 hr at 90 c, 24 hr at room temperature (ancamine 2167 curing agent)
Test system:	DEA 2970 du Pont
Temperature:	28 C
Humidity:	50% RH

Dielectric Constant

	20% SF14, DER 324	E-Glass
100 Hz	3.23	2.51
1 kHz	3.11	2.49
10 kHz	2.90	2.40
100 kHz	3.02	2.50

Table 4.23 20%-SF14/DER 324 matrix Dielectric constant

	Model		Data				
	Low	High	sample 1	sample 2	sample 3	sample 4	sample 5
100 Hz	2.96	3.01	2.73	3.19	2.71	2.84	2.65
1 kHz	2.89	2.92	2.65	3.09	2.65	2.74	2.54
10 kHz	2.73	2.75	2.45	2.91	2.45	2.56	2.39
100 kHz	2.84	2.86	2.66	3.02	2.64	2.71	2.60

Table 4.24 20%-SF14/DER 324-E-glass matrix Dielectric constant

Composite:	**DER 324 with 20% SF14 and 30% E-glass fibers**
Curing process:	7 hr at 90 c, 24 hr at room temperature (ancamine 2167 curing agent)
Test system:	DEA 2970 du Pont
Temperature:	28 C
Humidity:	50% RH

Loss Tangent

	20% SF14 DER324 Low	High	E-Glass
100 Hz	0.0354	0.0355	0.014
1 kHz	0.0192	0.0194	0.006
10 kHz	0.0160	0.0162	0.003
100 kHz	0.0209	0.0210	0.005

Table 4.25 20%-SF14/DER 324 matrix Loss Tangent

	Model Low 1	High 1	Data sample 1	sample 2	sample 3	sample 4	sample 5
100 Hz	0.0289	0.0290	0.0231	0.0243	0.0197	0.0222	0.0211
1 kHz	0.0152	0.0153	0.0138	0.0167	0.0125	0.0144	0.0151
10 kHz	0.0121	0.0121	0.0105	0.0147	0.0111	0.0106	0.0121
100 kHz	0.0161	0.0161	0.0142	0.0154	0.0136	0.0133	0.0171

Table 4.26 20%-SF14/DER 324-E-glass matrix Loss Tangent

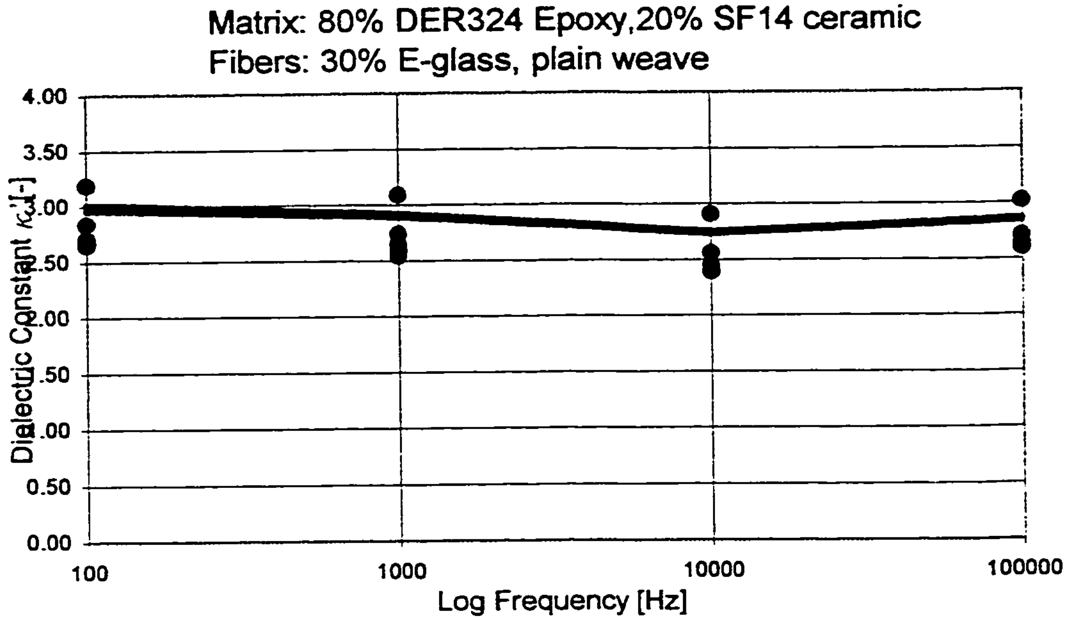

Figure 4.22 Dielectric Constant of 3-Phase composite
(Solid line - Prediction, Dots - Experiment)

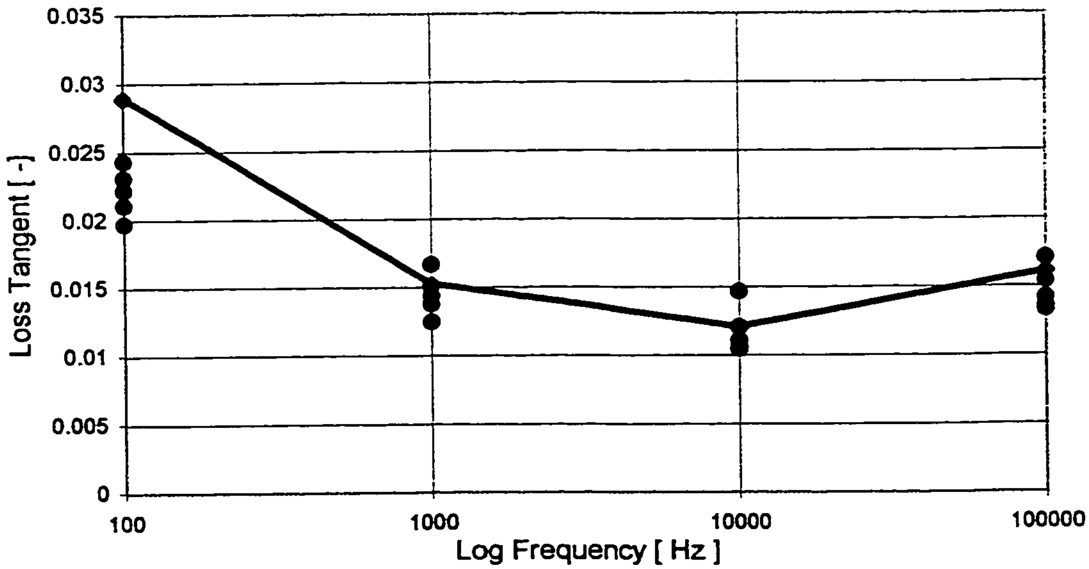

Figure 4.23 Loss tangent of 3-Phase composite
(Solid line - Prediction, Dots - Experiment)

Composite:	**DER 324 with 40% SF14 and 30% E-glass fibers**
Curing process:	7 hr at 90 c, 24 hr at room temperature (ancamine 2167 curing agent)
Test system:	DEA 2970 du Pont
Temperature:	28 C
Humidity:	50% RH

Dielectric Constant

	40% SF14, DER 324	E-Glass
100 Hz	3.13	2.51
1 kHz	2.94	2.49
10 kHz	2.70	2.40
100 kHz	2.85	2.50

Table 4.27 40%-SF14/DER 324 matrix Dielectric constant

	Model		Data				
	Low	High	sample 1	sample 2	sample 3	sample 4	sample 5
100 Hz	2.91	2.94	2.56	2.62	2.74	2.57	2.68
1 kHz	2.79	2.81	2.38	2.42	2.56	2.44	2.49
10 kHz	2.60	2.61	2.19	2.20	2.31	2.26	2.37
100 kHz	2.74	2.75	2.30	2.32	2.46	2.39	2.41

Table 4.28 40%-SF14/DER 324-E-glass matrix Dielectric constant

Composite:	**DER 324 with 20% SF14 and 30% E-glass fibers**
Curing process:	7 hr at 90 c, 24 hr at room temperature (ancamine 2167 curing agent)
Test system:	DEA 2970 du Pont
Temperature:	28 C
Humidity:	50% RH

Loss Tangent

	40% SF14 DER324 Low	High	E-Glass
100 Hz	0.0664	0.0665	0.014
1 kHz	0.0305	0.0309	0.006
10 kHz	0.0178	0.0181	0.003
100 kHz	0.0205	0.0207	0.005

Table 4.29 20%-SF14/DER 324 matrix Loss Tangent

	Model		Data				
	Low 1	High 1	sample 1	sample 2	sample 3	sample 4	sample 5
100 Hz	0.0505	0.0507	0.0656	0.0745	0.0683	0.0711	0.0641
1 kHz	0.0231	0.0232	0.0349	0.0409	0.0378	0.0425	0.0375
10 kHz	0.0133	0.0134	0.0195	0.0225	0.0229	0.0186	0.0199
100 kHz	0.0158	0.0159	0.0161	0.0189	0.0175	0.0188	0.0175

Table 4.30 40%-SF14/DER 324-E-glass matrix Loss Tangent

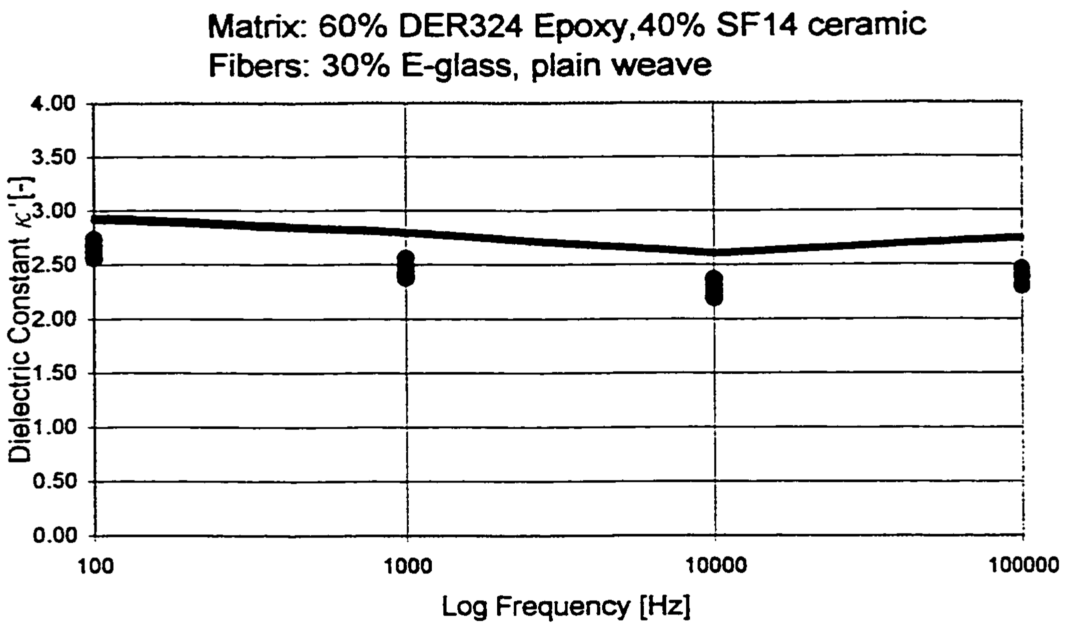

Figure 4.24 Dielectric Constant of 3-Phase composite
(Solid line - Prediction, Dots - Experiment)

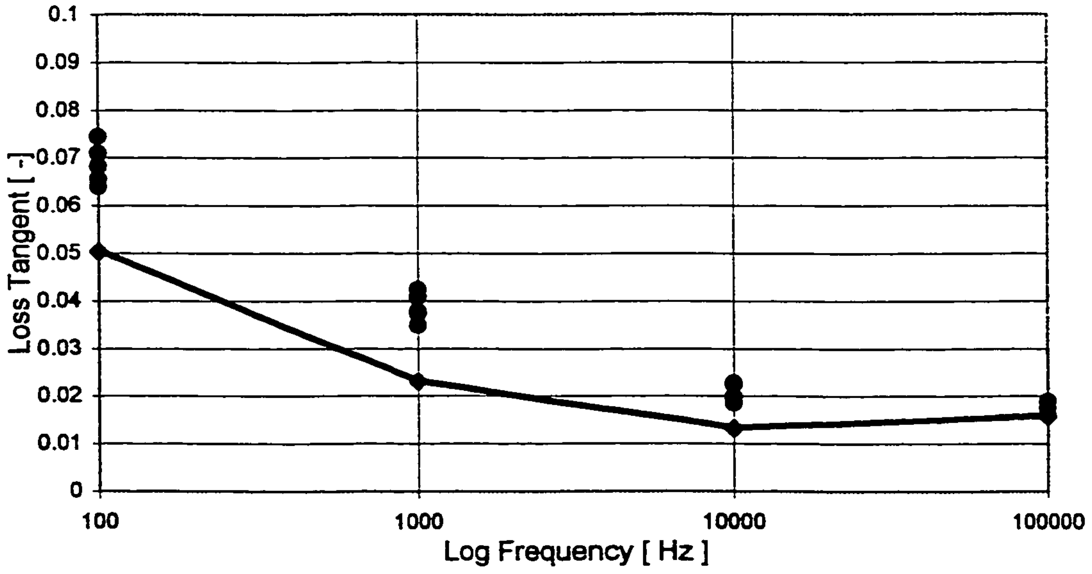

Figure 4.25 Loss tangent of 3-Phase composite
(Solid line - Prediction, Dots - Experiment)

CHAPTER 5

Discussion

The effective dielectric constant of the epoxy/hollow ceramic spheres composite system decreases with the increase of the hollow ceramic spheres volume fraction in the mixture. This decreasing tendency is observed throughout all the frequency range of the investigation that is in 100 Hz to 100 kHz. This result was expected since the hollow ceramic spheres used for this system have initially lower dielectric constant than epoxy matrix alone. The density analysis of the hollow ceramic spheres showed that the ceramic wall thickness is 5-8μm, and the average radius of the hollow sphere/air system is 50μm. These values indicate small volume fraction of the ceramics in the hollow ceramic sphere/ air system and they justify the initial low value of dielectric constant of hollow ceramic spheres observed in this study.

The decrease of the effective dielectric constant of the composite with increase of frequency of applied field was predicted and experimentally obtained in the frequency range 100 Hz - 10 kHz. Increase of the effective dielectric constant value was observed at 100 kHz. Above the frequency, which impedes the orientation of the dipoles in the composite, the decrease of the effective dielectric is expected. That frequency can not be determined using the DEA 2970 dielectric analyzer, since the range of the operation of this apparatus is up to 100 kHz. Evaluation of this frequency is subject to future studies of this composite system.. Similar approach is recommended using the different test equipment capable of generating the alternating applied fields of higher frequencies (up to 100 GHz).

The model used to predict the effective dielectric constant of epoxy/hollow ceramic spheres was based on the Clausius-Mossoti theory. Predicted values correlate well with the verified model for all frequencies tested. Better correlation is observed at higher frequencies (above 10 kHz) and also the experimental data is less scattered at higher frequencies. Better correlation between the experimental data and Clausius-Mossoti theory, when applied to epoxy/hollow ceramic sphere composite system is observed at low volume fractions of the hollow ceramic inclusions (below 30% volume fraction of hollow ceramic spheres) in the mixture. Above this volume fraction the effect of local field becomes more apparent which results in deviation from the Clausius-Mossoti equation. If the solid ceramics spheres were used, it would be reasonable to conclude that the increase of effective dielectric constant of the epoxy/solid ceramic spheres would increase with the increase of the volume fraction of the solid ceramic spheres in the mixture.

One of the objectives of this research was to establish methods for effective dielectric constant reduction. Based on theoretical and experimental results obtained by analyzing the epoxy/hollow ceramic sphere composite system, it can be concluded that, the introduction of the hollow ceramic spheres successfully reduces initially high dielectric constant of the epoxy matrix. Bearing in mind the possible aerospace application of composites produced by this method, it is worth noting that the density reduction is also observed. The density of the of the epoxy/hollow ceramic spheres composite system decreases with the increase of the hollow ceramic volume fraction in the mixture. The decrease of the impact strength of the epoxy/hollow ceramic spheres composite system with the increase of the spheres volume fraction was observed during samples manufacturing. E-glass fibers were added to this composite system, to improve impact strength and reduce CTE.

The DER 324 epoxy used as a matrix polymer (diglycidyl ether of bisphenol A, cycloaliphatic amine cured) used in this study contains highly polar molecular groups in its structure. This results in initially high values of loss tangent, which was observed when all DER 324 matrix based composite systems were tested. The loss tangent of the epoxy/ hollow ceramic system increases with the hollow ceramic spheres volume fraction and decreases with frequency in the 100 Hz to 100 kHz range.

A model used to predict loss tangent of the epoxy/hollow ceramic system was based on the Hashin-Schulgasser theory. This Model predicts bounds on loss tangent for composite system. In this particular case the data scatter was larger than the bounds predicted, therefore it is not conclusive whether the system behavior is following the lower or the higher bound for effective loss tangent of composite system, using this theory.

Prager's equations (3.30) were used to predict coefficients required by Hashin-Schulgasser theory in the effective loss tangent model for epoxy/hollow ceramic spheres system. If these equations are replaced with the equations suggested also by Hashin [18] same results are obtained for this composite system. The difference becomes more apparent with the high ratios of initial loss tangent of the constituents. The accuracy of the model for the effective loss tangent suggested by Hashin-Schulgasser, used in this study, is highly dependant on the accuracy of the measurement of the loss tangent of the constituents that will compose the composite mixture. To evaluate the loss tangent of the hollow ceramic spheres, required by this theory, the special set of samples was manufactured. These samples contained high volume fraction of the hollow ceramic spheres in the epoxy matrix (90%). This approach induced initial error, which was observed when the composite system was evaluated. The measurement of the loss tangent and dielectric constant of the hollow ceramic spheres alone is not feasible using DEA 2970 dielectric analyzer, since the spheres are supplied in the powder form.

To reduce initially high loss tangent of the matrix, polymers that are different from epoxy have to be used. The good candidate for this application is polystyrene or high density polyethylene polymer. These polymers have non-polar structure which results in low values for loss-tangent.

The model used to predict effective dielectric constant of the epoxy/ system was based on Wiener equations (3.28). Based on the dielctric constants of the constituents, which have very low ratio for this system, the model yielded close bounds, and the data scatter was larger than the bounds predicted. This occurrence was observed for all the fiber volume fractions (30 - 40 %) investigated in this research for all the frequencies of investigation. At the higher fiber volume fraction the measured effective dielectric constant of the epoxy/E-glass system is lower than predicted value based on this model. The estimate of the loss tangent based on the Hashin-Schulgasser theory, equations (3.28 to3.31), was higher than measured effective loss tangent for epoxy/E-glass system. The higher deviation from the model is observed at 100 kHz.

The '2 step modeling' approach is used to predict the effective constant and effective loss tangent for the multiphase composite which consisted of epoxy/hollow ceramic spheres with E-glass fibers. Better correlation between experimental and analytical data was observed when the epoxy matrix was modified with lower volume fraction of the hollow ceramic spheres (20%). At higher volume fractions of the hollow ceramic spheres in the epoxy matrix the model yielded lower values for effective constant and effective loss tangent. This result is expected since the accuracy of the model used to predict the dielectric properties of epoxy/hollow ceramic spheres system, deteriorates with the increase of the hollow ceramic in the epoxy, due to more apparent effects of the local field.

The complete set of estimated dielectric properties for composite systems investigated in this work is given in the Appendix.

CHAPTER 6

Conclusion

In summary, based on the theoretical and analytical analysis performed in this study it can be concluded that artificial dielectrics, with tailored dielectric properties, can be designed and manufactured. To achieve this goal polymer matrix composite materials can be used. Depending on the intended application of the material several factors have to be considered, and compromises have to be made. For satellite communication applications, where low dielectric constant and low loss tangent are required, non-polar polymers are required. Change in the effective dielectric constant of polymer based materials can be successfully achieved by mixing the matrix material, with ceramic inclusions and continuous fibers, and the dielectric properties of the composite can be estimated using the methodology presented in this research. A computer software was developed to enable the prediction of dielectric properties of polymer matrix composites.

6.1 Recommended Dielectric Models for Polymer Matrix Composites

Based on the experimental work done in this project following models can be recommended:

- Prediction of dielectric constant for composite systems with spherical inclusion in the epoxy matrix based on Clausius-Mossoti (equation 3.25) relation is recommended for these composite systems. It accurately predicts dielectric constant in the whole frequency range of investigation conducted in this research (100 Hz to 100 kHz).

- Prediction of dielectric constant for composite systems containing continuous fibers (epoxy/E-glass in this research) based on equation (3.28) has limited application, since it is not conclusive which bound yields better prediction for the dielectric constant.

- Prediction of the dielectric constant for multi-phase systems based on the 2-step approach (equations 3.25 and 3.28), is currently the only available model for dielectric constant for these systems. Its application is recommended for the initial analysis. For more accurate prediction testing has to be done.

- Prediction of the Loss tangent based on the Hashin-Schulgasser theory using Prager's coefficients (equations 3.25 and 3.28 to 3.31) is recommended for systems with spherical inclusions where the inclusion volume fraction is below 30%. Use of this model is also applicable to the multiphase composites for the frequency of applied field above 100 kHz.

6.2 Contribution

Contributions to the dielectric analysis of polymer composite materials obtained by this work are summarized as follows:

- Experimental dielectric data collection for Epoxy/Ceramic, Epoxy/E-glass and Epoxy/Ceramic/E-glass systems over the 100 Hz to 100 kHz frequency range.
- Assessment of currently available dielectric models for prediction of effective dielectric constant and effective loss tangent and their application to the polymer matrix composites.
- Prediction of the effective dielectric constant and effective loss tangent for the multiphase polymer composite systems.

6.3 Recommendation for Future Work

To obtain the composite system with the low effective loss tangent non polar polymer matrix has to be used. Polystyrene polymer satisfies this requirement and it is commercially available. To modify the dielectric constant of the polystyrene the hollow ceramic spheres can be embedded into the matrix. This approach will reduce the density and effective dielectric constant of this material and increase loss tangent when compared to polystyrene based polymers. To reduce CTE of this material fibers have to be embedded into the structure. If the prime interest is to obtain the composite structure with lowest loss tangent the E-glass fibers are recommended, because of their initial low loss tangent when compared to other commercially available fibers. If on the other hand, the density reduction is sought with the increase of impact resistance, the aramid based fibers can be used. Use of aramid fibers will increase the loss tangent of the composite when compared to E-glass.

When epoxy/amine systems are used more experimental work is required to determine the effects of amine content in the epoxy/amine system on the dielectric properties of the composite system as a function of the frequency and temperature, and its impact on mechanical properties of the cured system.

More experimental work is required for all the composite materials at frequencies higher than 100 kHz . The desirable range of investigation, which is of interest for the satellite communication industry is 30 - 60 GHz. Special equipment is required for this type of analysis. Experimental work is also required to estimate the change in the impact resistance of multiphase composites since no analytical models exist for this type of property analysis.

Theoretical prediction of the dielectric properties of polystyrene based composites is given in Tables 6.1 and 6.2, Figures 6.1 to 6.4 to assist the future investigation of the dielectric behavior of polymer based composites.

File run ID: Tue Nov 17 13:00:58 1998

Permittivity Analysis:
Polystyrene with SF14 hollow ceramic spheres
Fiber type: Spherical inclusions
Reference temperature: 28 [C]

Ematrix: 2.530000
Efiber: 2.380000

No:	Vs:	Vm:	Eeff:
0	0.000000	1.000000	2.530000
1	0.050000	0.950000	2.522356
2	0.100000	0.900000	2.514727
3	0.150000	0.850000	2.507113
4	0.200000	0.800000	2.499514
5	0.250000	0.750000	2.491930
6	0.300000	0.700000	2.484361
7	0.350000	0.650000	2.476807
8	0.400000	0.600000	2.469268
9	0.450000	0.550000	2.461745
10	0.500000	0.500000	2.454236
11	0.550000	0.450000	2.446743
12	0.600000	0.400000	2.439265
13	0.650000	0.350000	2.431803
14	0.700000	0.300000	2.424356
15	0.750000	0.250000	2.416924
16	0.800000	0.200000	2.409508
17	0.850000	0.150000	2.402108
18	0.900000	0.100000	2.394723
19	0.950000	0.050000	2.387354
20	1.000000	0.000000	2.380000

Density Analysis:
Polystyrene with SF14 hollow ceramic spheres
ROmatrix 1.050000
ROsphere: 0.700000

No:	Vs:	Vm:	Density:
0	0.000000	1.000000	1.050000
1	0.050000	0.950000	1.032500
2	0.100000	0.900000	1.015000
3	0.150000	0.850000	0.997500
4	0.200000	0.800000	0.980000
5	0.250000	0.750000	0.962500
6	0.300000	0.700000	0.945000
7	0.350000	0.650000	0.927500
8	0.400000	0.600000	0.910000
9	0.450000	0.550000	0.892500
10	0.500000	0.500000	0.875000
11	0.550000	0.450000	0.857500

Table 6.1 Polystyrene/SF 14 estimated dielectric properties at 100 kHz
(to be continued)

12	0.600000	0.400000	0.840000
13	0.650000	0.350000	0.822500
14	0.700000	0.300000	0.805000
15	0.750000	0.250000	0.787500
16	0.800000	0.200000	0.770000
17	0.850000	0.150000	0.752500
18	0.900000	0.100000	0.735000
19	0.950000	0.050000	0.717500
20	1.000000	0.000000	0.700000

Loss Tangent Analysis - DERIVATIVES:
Polystyrene with SF14 hollow ceramic spheres
Fiber type: Spherical inclusions
Reference temperature: 28 [C]

No:	Vs:	Low D1:	High D1	Low D2	High D2
1	0.050000	0.948084	0.948122	0.051936	0.051977
2	0.100000	0.896367	0.896440	0.103670	0.103747
3	0.150000	0.844851	0.844954	0.155202	0.155311
4	0.200000	0.793535	0.793664	0.206531	0.206669
5	0.250000	0.742419	0.742571	0.257658	0.257819
6	0.300000	0.691505	0.691675	0.308581	0.308762
7	0.350000	0.640793	0.640976	0.359301	0.359497
8	0.400000	0.590282	0.590475	0.409818	0.410023
9	0.450000	0.539973	0.540172	0.460130	0.460342
10	0.500000	0.489866	0.490068	0.510237	0.510451
11	0.550000	0.439963	0.440162	0.560140	0.560352
12	0.600000	0.390262	0.390455	0.609838	0.610043
13	0.650000	0.340765	0.340947	0.659330	0.659524
14	0.700000	0.291471	0.291639	0.708617	0.708796
15	0.750000	0.242381	0.242531	0.757697	0.757857
16	0.800000	0.193496	0.193624	0.806572	0.806708
17	0.850000	0.144814	0.144916	0.855239	0.855348
18	0.900000	0.096338	0.096410	0.903700	0.903777
19	0.950000	0.048066	0.048104	0.951954	0.951994
20	1.000000	0.000000	0.000000	1.000000	1.000000

Table 6.1 Polystyrene/SF 14 estimated dielectric properties at 100 kHz
(to be continued)

Frequency: 100000.000000 [Hz]
Fiber type: Spherical inclusions
Reference temperature: 28 [C]

Matrix loss: 0.000120
Sphere loss: 0.019700

No:	Vs:	Vm:	Tan delta Bounds		Ave loss
1	0.050000	0.950000	0.001080	0.001080	0.001080
2	0.100000	0.900000	0.002041	0.002043	0.002042
3	0.150000	0.850000	0.003005	0.003007	0.003006
4	0.200000	0.800000	0.003971	0.003973	0.003972
5	0.250000	0.750000	0.004938	0.004941	0.004940
6	0.300000	0.700000	0.005908	0.005912	0.005910
7	0.350000	0.650000	0.006880	0.006884	0.006882
8	0.400000	0.600000	0.007854	0.007858	0.007856
9	0.450000	0.550000	0.008830	0.008834	0.008832
10	0.500000	0.500000	0.009808	0.009812	0.009810
11	0.550000	0.450000	0.010788	0.010792	0.010790
12	0.600000	0.400000	0.011770	0.011774	0.011772
13	0.650000	0.350000	0.012755	0.012758	0.012757
14	0.700000	0.300000	0.013741	0.013744	0.013743
15	0.750000	0.250000	0.014729	0.014732	0.014731
16	0.800000	0.200000	0.015719	0.015722	0.015721
17	0.850000	0.150000	0.016711	0.016714	0.016713
18	0.900000	0.100000	0.017706	0.017707	0.017706
19	0.950000	0.050000	0.018702	0.018703	0.018702
20	1.000000	0.000000	0.019700	0.019700	0.019700

End of Analysis for Polystyrene with SF14 hollow ceramic spheres

Table 6.1 Polystyrene/SF 14 estimated dielectric properties at 100 kHz

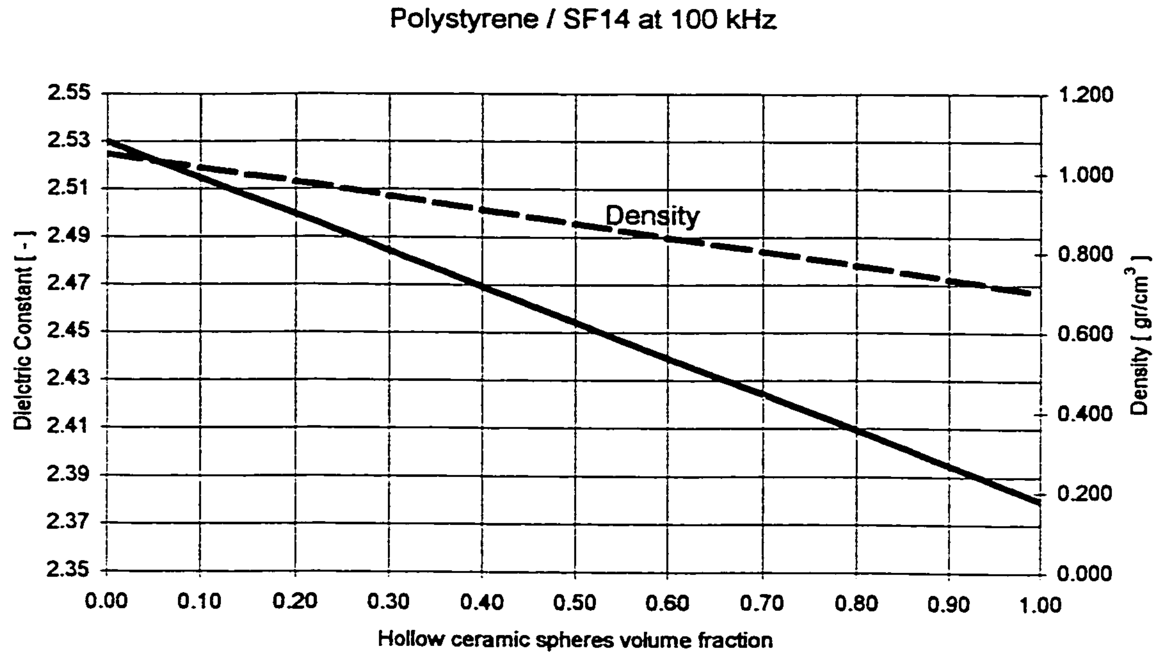

Figure 6.1 Polystyrene/SF14 Dielectric Constant Prediction at 100 kHz

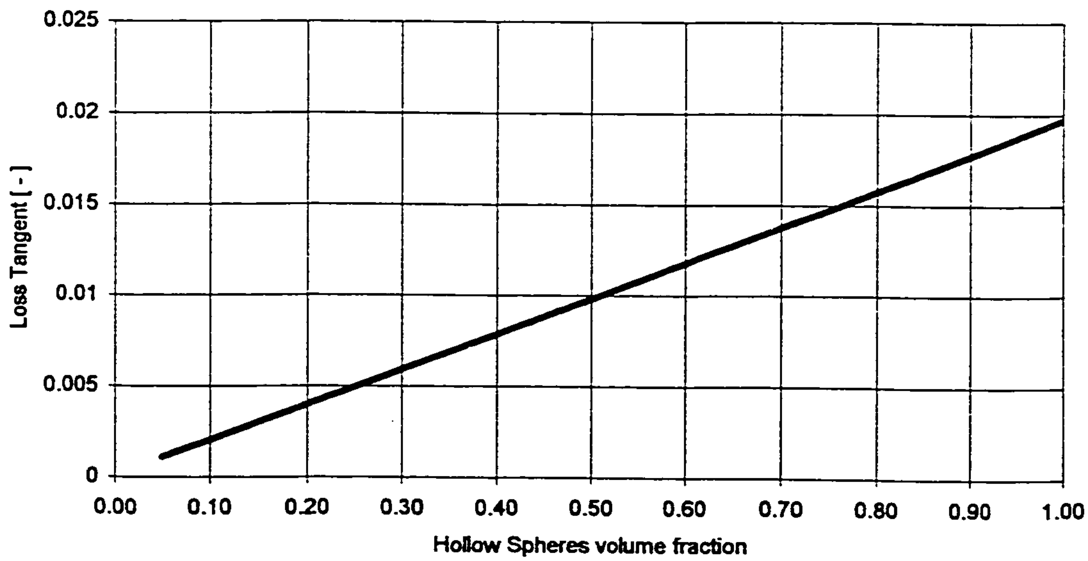

Figure 6.2 Polystyrene/SF14 Loss Tangent Prediction at 100 kHz

File run ID: Tue Nov 17 13:31:21 1998

Permittivity Analysis:
Polystyrene E-glass (plain weave)
Fiber type: Continous fibers
Reference temperature: 28 [C]

Ematrix: 2.530000
Efiber: 2.500000

No:	Vs:	Vm:	Elow:	Ehigh:	Eave:
0	0.000000	1.000000	2.530000	2.530000	2.530000
1	0.050000	0.950000	2.528483	2.528500	2.528491
2	0.100000	0.900000	2.526968	2.527000	2.526984
3	0.150000	0.850000	2.525454	2.525500	2.525477
4	0.200000	0.800000	2.523943	2.524000	2.523971
5	0.250000	0.750000	2.522433	2.522500	2.522466
6	0.300000	0.700000	2.520925	2.521000	2.520962
7	0.350000	0.650000	2.519418	2.519500	2.519459
8	0.400000	0.600000	2.517914	2.518000	2.517957
9	0.450000	0.550000	2.516411	2.516500	2.516456
10	0.500000	0.500000	2.514911	2.515000	2.514955
11	0.550000	0.450000	2.513411	2.513500	2.513456
12	0.600000	0.400000	2.511914	2.512000	2.511957
13	0.650000	0.350000	2.510419	2.510500	2.510459
14	0.700000	0.300000	2.508925	2.509000	2.508963
15	0.750000	0.250000	2.507433	2.507500	2.507467
16	0.800000	0.200000	2.505943	2.506000	2.505971
17	0.850000	0.150000	2.504455	2.504500	2.504477
18	0.900000	0.100000	2.502968	2.503000	2.502984
19	0.950000	0.050000	2.501483	2.501500	2.501492
20	1.000000	0.000000	2.500000	2.500000	2.500000

Density Analysis:
Polystyrene E-glass (plain weave)
ROmatrix 1.050000
ROsphere: 2.540000

No:	Vs:	Vm:	Density:
0	0.000000	1.000000	1.050000
1	0.050000	0.950000	1.124500
2	0.100000	0.900000	1.199000
3	0.150000	0.850000	1.273500
4	0.200000	0.800000	1.348000
5	0.250000	0.750000	1.422500
6	0.300000	0.700000	1.497000
7	0.350000	0.650000	1.571500
8	0.400000	0.600000	1.646000
9	0.450000	0.550000	1.720500
10	0.500000	0.500000	1.795000

Table 6.2 Polystyrene/E-glass estimated dielectric properties at 100 kHz
(to be continued)

11	0.550000	0.450000	1.869500
12	0.600000	0.400000	1.944000
13	0.650000	0.350000	2.018500
14	0.700000	0.300000	2.093000
15	0.750000	0.250000	2.167500
16	0.800000	0.200000	2.242000
17	0.850000	0.150000	2.316500
18	0.900000	0.100000	2.391000
19	0.950000	0.050000	2.465500
20	1.000000	0.000000	2.540000

Loss Tangent Analysis - DERIVATIVES:
Polystyrene E-glass (plain weave)
Fiber type: Continous fibers
Loss analysis based on AVE BOUNDS for Effective perimittivity
Reference temperature: 28 [C]

No:	Vs:	Low D1:	High D1	Low D2	High D2
1	0.050000	0.949430	0.949432	0.050571	0.050573
2	0.100000	0.898922	0.898925	0.101082	0.101085
3	0.150000	0.848473	0.848478	0.151531	0.151536
4	0.200000	0.798086	0.798091	0.201920	0.201926
5	0.250000	0.747758	0.747765	0.252248	0.252255
6	0.300000	0.697491	0.697499	0.302516	0.302524
7	0.350000	0.647284	0.647292	0.352724	0.352732
8	0.400000	0.597137	0.597146	0.402871	0.402880
9	0.450000	0.547050	0.547059	0.452959	0.452968
10	0.500000	0.497022	0.497031	0.502987	0.502996
11	0.550000	0.447054	0.447063	0.552954	0.552963
12	0.600000	0.397146	0.397154	0.602863	0.602871
13	0.650000	0.347296	0.347304	0.652712	0.652720
14	0.700000	0.297506	0.297514	0.702501	0.702509
15	0.750000	0.247775	0.247782	0.752232	0.752238
16	0.800000	0.198103	0.198108	0.801903	0.801909
17	0.850000	0.148489	0.148494	0.851515	0.851520
18	0.900000	0.098934	0.098938	0.901069	0.901072
19	0.950000	0.049438	0.049440	0.950564	0.950565
20	1.000000	0.000000	0.000000	1.000000	1.000000

Table 6.2 Polystyrene/E-glass estimated dielectric properties at 100 kHz
(to be continued)

```
Frequency: 100000.000000 [Hz]
Fiber type: Continuos fibers
Loss analysis based on AVE BOUNDS for Effective perimittivity
Reference temperature:  28     [C]
Matrix loss:        0.000120
Sphere loss:        0.004500
```

No:	Vs:	Vm:	Tan delta Bounds		Ave loss
1	0.050000	0.950000	0.000339	0.000339	0.000339
2	0.100000	0.900000	0.000558	0.000558	0.000558
3	0.150000	0.850000	0.000777	0.000777	0.000777
4	0.200000	0.800000	0.000996	0.000996	0.000996
5	0.250000	0.750000	0.001215	0.001215	0.001215
6	0.300000	0.700000	0.001434	0.001434	0.001434
7	0.350000	0.650000	0.001653	0.001653	0.001653
8	0.400000	0.600000	0.001872	0.001872	0.001872
9	0.450000	0.550000	0.002091	0.002091	0.002091
10	0.500000	0.500000	0.002310	0.002310	0.002310
11	0.550000	0.450000	0.002529	0.002529	0.002529
12	0.600000	0.400000	0.002748	0.002748	0.002748
13	0.650000	0.350000	0.002967	0.002967	0.002967
14	0.700000	0.300000	0.003186	0.003186	0.003186
15	0.750000	0.250000	0.003405	0.003405	0.003405
16	0.800000	0.200000	0.003624	0.003624	0.003624
17	0.850000	0.150000	0.003843	0.003843	0.003843
18	0.900000	0.100000	0.004062	0.004062	0.004062
19	0.950000	0.050000	0.004281	0.004281	0.004281
20	1.000000	0.000000	0.004500	0.004500	0.004500

```
End of Analysis for Polystyrene E-glass ( plain weave)
```

Table 6.2 Polystyrene/E-glass estimated dielectric properties at 100 kHz

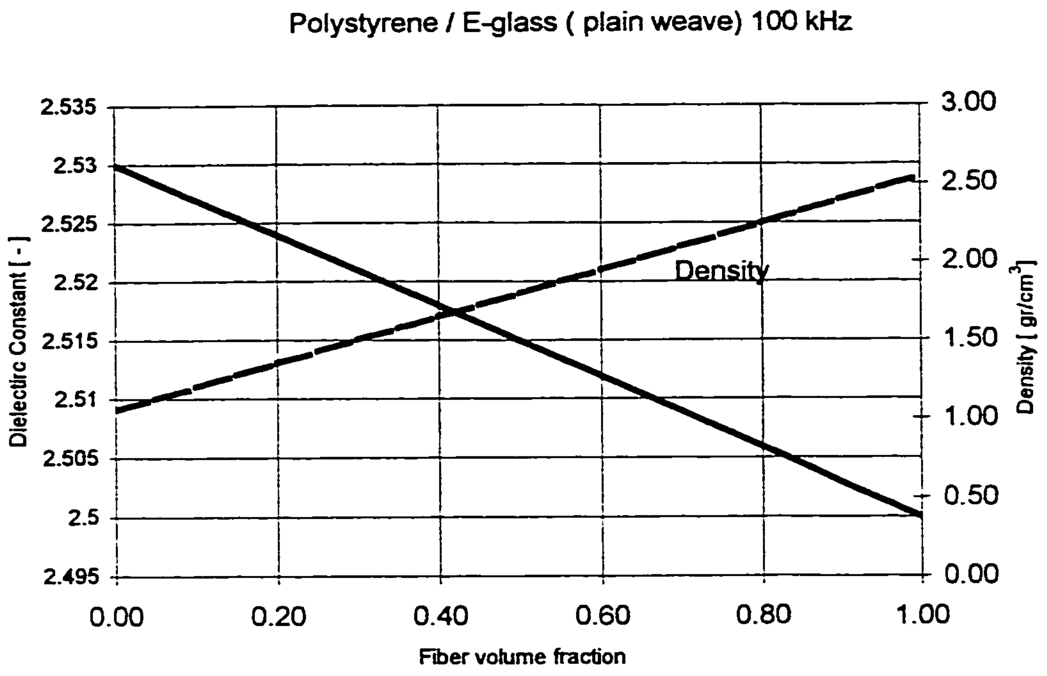

Figure 6.3 Polystyrene/E-glass Dielectric Constant Prediction at 100 kHz

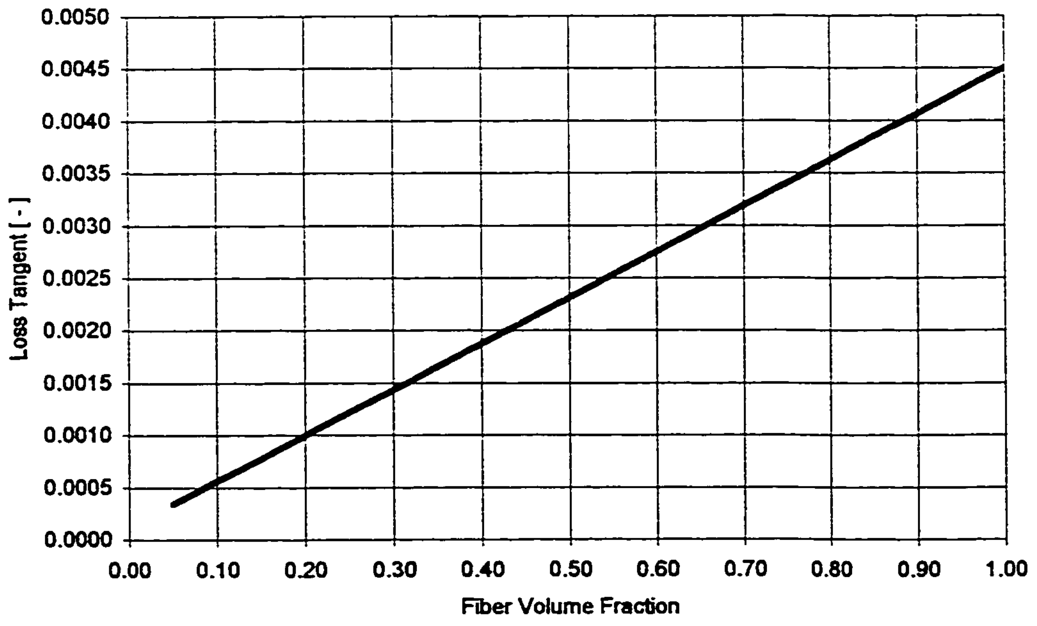

Figure 6.4 Polystyrene/E-Glass Loss Tangent Prediction at 100 kHz

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APPENDIX

Estimated Dielectric properties (computer output):

Equations used: 4.5 and 4.6

DER 324 / SF 14 at 100 kHz
DER 324 / SF 14 at 10 kHz
DER 324 / SF 14 at 1kHz
DER 324 / SF 14 at 100 Hz

Equations used: 4.7 and 4.6

DER 324/ E-glass at 100 kHz
DER 324/ E-glass at 10 kHz
DER 324/ E-glass at 1kHz
DER 324/ E-glass at 100 Hz

Equations used: 4.5, 4.6 and 4.7

DER 324/SF14/E-Glass at 100 kHz (20% SF14, 80% Epoxy)
DER 324/SF14/E-Glass at 10 kHz (20% SF14, 80% Epoxy)
DER 324/SF14/E-Glass at 1 kHz (20% SF14, 80% Epoxy)
DER 324/SF14/E-Glass at 100 kHz (20% SF14, 80% Epoxy)

DER 324/SF14/E-Glass at 100 kHz (40% SF14, 60% Epoxy)
DER 324/SF14/E-Glass at 10 kHz (40% SF14, 60% Epoxy)
DER 324/SF14/E-Glass at 1 kHz (40% SF14, 60% Epoxy)
DER 324/SF14/E-Glass at 100 kHz (40% SF14, 60% Epoxy)

File run ID: Wed Oct 21 14:37:42 1998

Permittivity Analysis:
2Phase: DER324 & SF14 at 100Khz
Fiber type: Spherical inclusions
Reference temperature: 28 [C]

Ematrix: 3.200000
Efiber: 2.380000

No:	Vs:	Vm:	Eeff:
0	0.000000	1.000000	3.200000
1	0.050000	0.950000	3.155342
2	0.100000	0.900000	3.111031
3	0.150000	0.850000	3.067074
4	0.200000	0.800000	3.023477
5	0.250000	0.750000	2.980247
6	0.300000	0.700000	2.937389
7	0.350000	0.650000	2.894912
8	0.400000	0.600000	2.852820
9	0.450000	0.550000	2.811120
10	0.500000	0.500000	2.769819
11	0.550000	0.450000	2.728923
12	0.600000	0.400000	2.688437
13	0.650000	0.350000	2.648367
14	0.700000	0.300000	2.608720
15	0.750000	0.250000	2.569500
16	0.800000	0.200000	2.530714
17	0.850000	0.150000	2.492366
18	0.900000	0.100000	2.454461
19	0.950000	0.050000	2.417004
20	1.000000	0.000000	2.380000

Loss Tangent Analysis - DERIVATIVES:
2Phase: DER324 & SF14 at 100Khz
Fiber type: Spherical inclusions
Reference temperature: 28 [C]

No:	Vs:	Low D1:	High D1	Low D2	High D2
1	0.050000	0.941099	0.941926	0.059320	0.060430
2	0.100000	0.883084	0.884644	0.117719	0.119817
3	0.150000	0.825963	0.828166	0.175186	0.178148
4	0.200000	0.769748	0.772502	0.231710	0.235414
5	0.250000	0.714448	0.717664	0.287279	0.291602
6	0.300000	0.660072	0.663660	0.341882	0.346705
7	0.350000	0.606630	0.610500	0.395509	0.400712
8	0.400000	0.554131	0.558195	0.448149	0.453614
9	0.450000	0.502581	0.506754	0.499794	0.505403
10	0.500000	0.451990	0.456184	0.550433	0.556072
11	0.550000	0.402363	0.406494	0.600059	0.605614
12	0.600000	0.353707	0.357692	0.648664	0.654022
13	0.650000	0.306029	0.309786	0.696240	0.701291
14	0.700000	0.259333	0.262781	0.742781	0.747417
15	0.750000	0.213625	0.216685	0.788281	0.792395
16	0.800000	0.168907	0.171503	0.832734	0.836223

17	0.850000	0.125184	0.127239	0.876135	0.878898
18	0.900000	0.082457	0.083898	0.918482	0.920419
19	0.950000	0.040729	0.041484	0.959771	0.960786
20	1.000000	0.000000	0.000000	1.000000	1.000000

Frequency: 100000.000000 [Hz]
Fiber type: Spherical inclusions
Reference temperature: 28 [C]

Matrix loss: 0.021200
Sphere loss: 0.019700

No:	Vs:	Vm:	Tan delta Bounds		Ave loss
1	0.050000	0.950000	0.021115	0.021149	0.021132
2	0.100000	0.900000	0.021031	0.021097	0.021064
3	0.150000	0.850000	0.020947	0.021041	0.020994
4	0.200000	0.800000	0.020865	0.020984	0.020924
5	0.250000	0.750000	0.020783	0.020924	0.020853
6	0.300000	0.700000	0.020702	0.020861	0.020782
7	0.350000	0.650000	0.020622	0.020797	0.020709
8	0.400000	0.600000	0.020543	0.020729	0.020636
9	0.450000	0.550000	0.020465	0.020659	0.020562
10	0.500000	0.500000	0.020388	0.020586	0.020487
11	0.550000	0.450000	0.020312	0.020510	0.020411
12	0.600000	0.400000	0.020238	0.020432	0.020335
13	0.650000	0.350000	0.020165	0.020351	0.020258
14	0.700000	0.300000	0.020094	0.020267	0.020180
15	0.750000	0.250000	0.020024	0.020180	0.020102
16	0.800000	0.200000	0.019956	0.020090	0.020023
17	0.850000	0.150000	0.019889	0.019997	0.019943
18	0.900000	0.100000	0.019824	0.019901	0.019863
19	0.950000	0.050000	0.019761	0.019802	0.019782
20	1.000000	0.000000	0.019700	0.019700	0.019700

End of Analysis for 2Phase: DER324 & SF14 at 100Khz

File run ID: Wed Oct 21 14:31:47 1998

Permittivity Analysis:
2Phase: DER324 & SF14 at 10 Khz
Fiber type: Spherical inclusions
Reference temperature: 28 [C]

Ematrix: 3.110000
Efiber: 2.160000

No:	Vs:	Vm:	Eeff:
0	0.000000	1.000000	3.110000
1	0.050000	0.950000	3.057349
2	0.100000	0.900000	3.005173
3	0.150000	0.850000	2.953483
4	0.200000	0.800000	2.902292
5	0.250000	0.750000	2.851611
6	0.300000	0.700000	2.801450
7	0.350000	0.650000	2.751823
8	0.400000	0.600000	2.702739
9	0.450000	0.550000	2.654211
10	0.500000	0.500000	2.606249
11	0.550000	0.450000	2.558864
12	0.600000	0.400000	2.512067
13	0.650000	0.350000	2.465867
14	0.700000	0.300000	2.420276
15	0.750000	0.250000	2.375302
16	0.800000	0.200000	2.330955
17	0.850000	0.150000	2.287243
18	0.900000	0.100000	2.244175
19	0.950000	0.050000	2.201758
20	1.000000	0.000000	2.160000

Loss Tangent Analysis - DERIVATIVES:
2Phase: DER324 & SF14 at 10 Khz
Fiber type: Spherical inclusions
Reference temperature: 28 [C]

No:	Vs:	Low D1:	High D1	Low D2	High D2
1	0.050000	0.939186	0.940403	0.061433	0.063185
2	0.100000	0.879430	0.881728	0.121759	0.125067
3	0.150000	0.820747	0.823990	0.180960	0.185629
4	0.200000	0.763155	0.767208	0.239017	0.244852
5	0.250000	0.706667	0.711396	0.295912	0.302720
6	0.300000	0.651300	0.656571	0.351626	0.359217
7	0.350000	0.597067	0.602749	0.406145	0.414327
8	0.400000	0.543981	0.549945	0.459450	0.468036
9	0.450000	0.492056	0.498172	0.511527	0.520332
10	0.500000	0.441303	0.447444	0.562361	0.571202
11	0.550000	0.391732	0.397774	0.611939	0.620637
12	0.600000	0.343354	0.349174	0.660248	0.668627
13	0.650000	0.296176	0.301655	0.707278	0.715166
14	0.700000	0.250207	0.255227	0.753019	0.760247
15	0.750000	0.205451	0.209899	0.797461	0.803865
16	0.800000	0.161914	0.165680	0.840598	0.846019
17	0.850000	0.119599	0.122575	0.882424	0.886708

18	0.900000	0.078509	0.080591	0.922934	0.925932
19	0.950000	0.038643	0.039731	0.962127	0.963694
20	1.000000	-0.000000	-0.000000	1.000000	1.000000

Frequency: 10000.000000 [Hz]
Fiber type: Spherical inclusions
Reference temperature: 28 [C]

Matrix loss: 0.014400
Sphere loss: 0.024000

No:	Vs:	Vm:	Tan delta Bounds		Ave loss
1	0.050000	0.950000	0.014799	0.014846	0.014823
2	0.100000	0.900000	0.015206	0.015297	0.015252
3	0.150000	0.850000	0.015621	0.015752	0.015687
4	0.200000	0.800000	0.016045	0.016212	0.016129
5	0.250000	0.750000	0.016478	0.016676	0.016577
6	0.300000	0.700000	0.016918	0.017143	0.017031
7	0.350000	0.650000	0.017368	0.017615	0.017491
8	0.400000	0.600000	0.017826	0.018090	0.017958
9	0.450000	0.550000	0.018293	0.018568	0.018431
10	0.500000	0.500000	0.018769	0.019050	0.018909
11	0.550000	0.450000	0.019253	0.019535	0.019394
12	0.600000	0.400000	0.019746	0.020023	0.019885
13	0.650000	0.350000	0.020248	0.020513	0.020381
14	0.700000	0.300000	0.020759	0.021006	0.020883
15	0.750000	0.250000	0.021278	0.021501	0.021390
16	0.800000	0.200000	0.021806	0.021998	0.021902
17	0.850000	0.150000	0.022342	0.022497	0.022419
18	0.900000	0.100000	0.022886	0.022997	0.022942
19	0.950000	0.050000	0.023439	0.023498	0.023469
20	1.000000	0.000000	0.024000	0.024000	0.024000

End of Analysis for 2Phase: DER324 & SF14 at 10 Khz

File run ID: Wed Oct 21 14:23:06 1998

Permittivity Analysis:
2Phase: DER324 & SF14 at 1Khz
Fiber type: Spherical inclusions
Reference temperature: 28 [C]

Ematrix: 3.290000
Efiber: 2.460000

No:	Vs:	Vm:	Eeff:
0	0.000000	1.000000	3.290000
1	0.050000	0.950000	3.244861
2	0.100000	0.900000	3.200067
3	0.150000	0.850000	3.155626
4	0.200000	0.800000	3.111544
5	0.250000	0.750000	3.067827
6	0.300000	0.700000	3.024481
7	0.350000	0.650000	2.981514
8	0.400000	0.600000	2.938930
9	0.450000	0.550000	2.896736
10	0.500000	0.500000	2.854939
11	0.550000	0.450000	2.813543
12	0.600000	0.400000	2.772556
13	0.650000	0.350000	2.731982
14	0.700000	0.300000	2.691828
15	0.750000	0.250000	2.652098
16	0.800000	0.200000	2.612799
17	0.850000	0.150000	2.573935
18	0.900000	0.100000	2.535510
19	0.950000	0.050000	2.497531
20	1.000000	0.000000	2.460000

Loss Tangent Analysis - DERIVATIVES:
2Phase: DER324 & SF14 at 1Khz
Fiber type: Spherical inclusions
Reference temperature: 28 [C]

No:	Vs:	Low D1:	High D1	Low D2	High D2
1	0.050000	0.941251	0.942049	0.059154	0.060222
2	0.100000	0.883372	0.884880	0.117403	0.119420
3	0.150000	0.826374	0.828503	0.174736	0.177583
4	0.200000	0.770267	0.772930	0.231140	0.234701
5	0.250000	0.715060	0.718169	0.286607	0.290764
6	0.300000	0.660762	0.664230	0.341124	0.345762
7	0.350000	0.607382	0.611123	0.394682	0.399686
8	0.400000	0.554928	0.558857	0.447272	0.452528
9	0.450000	0.503407	0.507441	0.498884	0.504279
10	0.500000	0.452828	0.456883	0.549509	0.554933
11	0.550000	0.403196	0.407191	0.599140	0.604483
12	0.600000	0.354519	0.358373	0.647768	0.652923
13	0.650000	0.306801	0.310435	0.695387	0.700247
14	0.700000	0.260048	0.263384	0.741990	0.746451
15	0.750000	0.214265	0.217226	0.787571	0.791531
16	0.800000	0.169455	0.171966	0.832126	0.835485
17	0.850000	0.125621	0.127610	0.875650	0.878309

18	0.900000	0.082767	0.084161	0.918138	0.920003
19	0.950000	0.040892	0.041623	0.959589	0.960567
20	1.000000	0.000000	0.000000	1.000000	1.000000

Frequency: 1000.000000 [Hz]
Fiber type: Spherical inclusions
Reference temperature: 28 [C]

Matrix loss: 0.008300
Sphere loss: 0.067800

No:	Vs:	Vm:	Tan delta Bounds		Ave loss
1	0.050000	0.950000	0.010962	0.011023	0.010992
2	0.100000	0.900000	0.013657	0.013775	0.013716
3	0.150000	0.850000	0.016386	0.016555	0.016471
4	0.200000	0.800000	0.019150	0.019364	0.019257
5	0.250000	0.750000	0.021947	0.022200	0.022074
6	0.300000	0.700000	0.024777	0.025064	0.024921
7	0.350000	0.650000	0.027642	0.027956	0.027799
8	0.400000	0.600000	0.030539	0.030874	0.030707
9	0.450000	0.550000	0.033470	0.033819	0.033645
10	0.500000	0.500000	0.036434	0.036790	0.036612
11	0.550000	0.450000	0.039430	0.039786	0.039608
12	0.600000	0.400000	0.042459	0.042807	0.042633
13	0.650000	0.350000	0.045520	0.045853	0.045687
14	0.700000	0.300000	0.048612	0.048923	0.048768
15	0.750000	0.250000	0.051736	0.052015	0.051876
16	0.800000	0.200000	0.054890	0.055130	0.055010
17	0.850000	0.150000	0.058074	0.058267	0.058171
18	0.900000	0.100000	0.061287	0.061425	0.061356
19	0.950000	0.050000	0.064530	0.064603	0.064566
20	1.000000	0.000000	0.067800	0.067800	0.067800

End of Analysis for 2Phase: DER324 & SF14 at 1Khz

File run ID: Wed Oct 21 14:10:40 1998

Permittivity Analysis:
2Phase: DER324 and SF14 at 100 Hz
Fiber type: Spherical inclusions
Reference temperature: 28 [C]

Ematrix: 3.320000
Efiber: 2.870000

No:	Vs:	Vm:	Eeff:
0	0.000000	1.000000	3.320000
1	0.050000	0.950000	3.296486
2	0.100000	0.900000	3.273074
3	0.150000	0.850000	3.249764
4	0.200000	0.800000	3.226558
5	0.250000	0.750000	3.203456
6	0.300000	0.700000	3.180460
7	0.350000	0.650000	3.157569
8	0.400000	0.600000	3.134785
9	0.450000	0.550000	3.112109
10	0.500000	0.500000	3.089541
11	0.550000	0.450000	3.067083
12	0.600000	0.400000	3.044734
13	0.650000	0.350000	3.022497
14	0.700000	0.300000	3.000371
15	0.750000	0.250000	2.978357
16	0.800000	0.200000	2.956456
17	0.850000	0.150000	2.934670
18	0.900000	0.100000	2.912997
19	0.950000	0.050000	2.891441
20	1.000000	0.000000	2.870000

Loss Tangent Analysis - DERIVATIVES:
2Phase: DER324 and SF14 at 100 Hz
Fiber type: Spherical inclusions
Reference temperature: 28 [C]

No:	Vs:	Low D1:	High D1	Low D2	High D2
1	0.050000	0.945498	0.945711	0.054608	0.054854
2	0.100000	0.891459	0.891860	0.108745	0.109209
3	0.150000	0.837884	0.838451	0.162406	0.163063
4	0.200000	0.784775	0.785486	0.215590	0.216413
5	0.250000	0.732135	0.732966	0.268295	0.269257
6	0.300000	0.679966	0.680895	0.320519	0.321593
7	0.350000	0.628269	0.629273	0.372259	0.373420
8	0.400000	0.577047	0.578103	0.423513	0.424735
9	0.450000	0.526301	0.527388	0.474279	0.475537
10	0.500000	0.476033	0.477129	0.524555	0.525823
11	0.550000	0.426245	0.427327	0.574340	0.575592
12	0.600000	0.376939	0.377985	0.623632	0.624842
13	0.650000	0.328116	0.329105	0.672428	0.673572
14	0.700000	0.279777	0.280688	0.720727	0.721780
15	0.750000	0.231925	0.232736	0.768527	0.769465
16	0.800000	0.184560	0.185250	0.815827	0.816626

17	0.850000	0.137684	0.138233	0.862626	0.863261
18	0.900000	0.091298	0.091684	0.908922	0.909369
19	0.950000	0.045403	0.045606	0.954714	0.954949
20	1.000000	-0.000000	-0.000000	1.000000	1.000000

Frequency: 100.000000 [Hz]
Fiber type: Spherical inclusions
Reference temperature: 28 [C]

Matrix loss: 0.005000
Sphere loss: 0.163300

No:	Vs:	Vm:	Tan delta Bounds		Ave loss
1	0.050000	0.950000	0.012525	0.012561	0.012543
2	0.100000	0.900000	0.020092	0.020161	0.020127
3	0.150000	0.850000	0.027702	0.027799	0.027750
4	0.200000	0.800000	0.035353	0.035476	0.035414
5	0.250000	0.750000	0.043046	0.043191	0.043118
6	0.300000	0.700000	0.050781	0.050944	0.050862
7	0.350000	0.650000	0.058556	0.058734	0.058645
8	0.400000	0.600000	0.066374	0.066562	0.066468
9	0.450000	0.550000	0.074232	0.074427	0.074329
10	0.500000	0.500000	0.082131	0.082329	0.082230
11	0.550000	0.450000	0.090070	0.090267	0.090169
12	0.600000	0.400000	0.098050	0.098242	0.098146
13	0.650000	0.350000	0.106069	0.106252	0.106161
14	0.700000	0.300000	0.114129	0.114298	0.114213
15	0.750000	0.250000	0.122227	0.122379	0.122303
16	0.800000	0.200000	0.130365	0.130495	0.130430
17	0.850000	0.150000	0.138541	0.138646	0.138594
18	0.900000	0.100000	0.146756	0.146830	0.146793
19	0.950000	0.050000	0.155009	0.155049	0.155029
20	1.000000	0.000000	0.163300	0.163300	0.163300

End of Analysis for 2Phase: DER324 and SF14 at 100 Hz

File run ID: Sun Nov 08 12:48:16 1998

Permittivity Analysis:
Eglass/Epoxy (plain weave mat) at 100 kHz
Fiber type: Continuous fibers
Reference temperature: 28 [C]

Ematrix: 3.200000
Efiber: 2.500000

No:	Vs:	Vm:	Elow:	Ehigh:	Eave:
0	0.000000	1.000000	3.200000	3.200000	3.200000
1	0.050000	0.950000	3.155819	3.165000	3.160409
2	0.100000	0.900000	3.112840	3.130000	3.121420
3	0.150000	0.850000	3.071017	3.095000	3.083009
4	0.200000	0.800000	3.030303	3.060000	3.045152
5	0.250000	0.750000	2.990654	3.025000	3.007827
6	0.300000	0.700000	2.952030	2.990000	2.971015
7	0.350000	0.650000	2.914390	2.955000	2.934695
8	0.400000	0.600000	2.877698	2.920000	2.898849
9	0.450000	0.550000	2.841918	2.885000	2.863459
10	0.500000	0.500000	2.807018	2.850000	2.828509
11	0.550000	0.450000	2.772964	2.815000	2.793982
12	0.600000	0.400000	2.739726	2.780000	2.759863
13	0.650000	0.350000	2.707276	2.745000	2.726138
14	0.700000	0.300000	2.675585	2.710000	2.692793
15	0.750000	0.250000	2.644628	2.675000	2.659814
16	0.800000	0.200000	2.614379	2.640000	2.627190
17	0.850000	0.150000	2.584814	2.605000	2.594907
18	0.900000	0.100000	2.555911	2.570000	2.562955
19	0.950000	0.050000	2.527646	2.535000	2.531323
20	1.000000	0.000000	2.500000	2.500000	2.500000

Loss Tangent Analysis - DERIVATIVES:
Eglass/Epoxy (plain weave mat) at 100 kHz
Fiber type: Continuos fibers
Loss analysis based on AVE BOUNDS for Effective permittivity
Reference temperature: 28 [C]

No:	Vs:	Low D1:	High D1	Low D2	High D2
1	0.050000	0.936929	0.937646	0.063977	0.064895
2	0.100000	0.875653	0.876994	0.126016	0.127732
3	0.150000	0.816084	0.817958	0.186217	0.188616
4	0.200000	0.758138	0.760458	0.244674	0.247644
5	0.250000	0.701737	0.704420	0.301473	0.304907
6	0.300000	0.646807	0.649774	0.356696	0.360493
7	0.350000	0.593280	0.596453	0.410419	0.414480
8	0.400000	0.541090	0.544395	0.462714	0.466944
9	0.450000	0.490176	0.493542	0.513650	0.517958
10	0.500000	0.440482	0.443840	0.563289	0.567587
11	0.550000	0.391951	0.395236	0.611691	0.615895
12	0.600000	0.344535	0.347681	0.658913	0.662941
13	0.650000	0.298183	0.301130	0.705009	0.708781
14	0.700000	0.252850	0.255539	0.750027	0.753469

15	0.750000	0.208494	0.210867	0.794016	0.797053
16	0.800000	0.165073	0.167075	0.837020	0.839582
17	0.850000	0.122549	0.124126	0.879081	0.881100
18	0.900000	0.080885	0.081986	0.920240	0.921649
19	0.950000	0.040046	0.040621	0.960535	0.961270
20	1.000000	0.000000	0.000000	1.000000	1.000000

Frequency: 100000.000000 [Hz]
Fiber type: Continuos fibers
Loss analysis based on AVE BOUNDS for Effective permittivity
Reference temperature: 28 [C]

Matrix loss: 0.021200
Sphere loss: 0.004500

No:	Vs:	Vm:	Tan delta Bounds		Ave loss
1	0.050000	0.950000	0.020339	0.020358	0.020349
2	0.100000	0.900000	0.019485	0.019521	0.019503
3	0.150000	0.850000	0.018637	0.018687	0.018662
4	0.200000	0.800000	0.017794	0.017856	0.017825
5	0.250000	0.750000	0.016955	0.017028	0.016992
6	0.300000	0.700000	0.016120	0.016202	0.016161
7	0.350000	0.650000	0.015288	0.015377	0.015332
8	0.400000	0.600000	0.014459	0.014552	0.014505
9	0.450000	0.550000	0.013631	0.013728	0.013679
10	0.500000	0.500000	0.012805	0.012903	0.012854
11	0.550000	0.450000	0.011980	0.012077	0.012028
12	0.600000	0.400000	0.011155	0.011249	0.011202
13	0.650000	0.350000	0.010330	0.010419	0.010374
14	0.700000	0.300000	0.009504	0.009586	0.009545
15	0.750000	0.250000	0.008676	0.008750	0.008713
16	0.800000	0.200000	0.007847	0.007909	0.007878
17	0.850000	0.150000	0.007015	0.007065	0.007040
18	0.900000	0.100000	0.006180	0.006216	0.006198
19	0.950000	0.050000	0.005342	0.005361	0.005352
20	1.000000	0.000000	0.004500	0.004500	0.004500

End of Analysis for Eglass/Epoxy (plain weave mat) at 100 kHz

File run ID: Sun Nov 08 12:46:40 1998

Permittivity Analysis:
Eglass/Epoxy (plain weave mat) at 10 kHz
Fiber type: Continuous fibers
Reference temperature: 28 [C]

Ematrix: 3.110000
Efiber: 2.400000

No:	Vs:	Vm:	Elow:	Ehigh:	Eave:
0	0.000000	1.000000	3.110000	3.110000	3.110000
1	0.050000	0.950000	3.064668	3.074500	3.069584
2	0.100000	0.900000	3.020639	3.039000	3.029820
3	0.150000	0.850000	2.977858	3.003500	2.990679
4	0.200000	0.800000	2.936271	2.968000	2.952135
5	0.250000	0.750000	2.895829	2.932500	2.914165
6	0.300000	0.700000	2.856487	2.897000	2.876743
7	0.350000	0.650000	2.818199	2.861500	2.839849
8	0.400000	0.600000	2.780924	2.826000	2.803462
9	0.450000	0.550000	2.744622	2.790500	2.767561
10	0.500000	0.500000	2.709256	2.755000	2.732128
11	0.550000	0.450000	2.674789	2.719500	2.697145
12	0.600000	0.400000	2.641189	2.684000	2.662594
13	0.650000	0.350000	2.608422	2.648500	2.628461
14	0.700000	0.300000	2.576458	2.613000	2.594729
15	0.750000	0.250000	2.545269	2.577500	2.561384
16	0.800000	0.200000	2.514825	2.542000	2.528412
17	0.850000	0.150000	2.485101	2.506500	2.495800
18	0.900000	0.100000	2.456071	2.471000	2.463536
19	0.950000	0.050000	2.427712	2.435500	2.431606
20	1.000000	0.000000	2.400000	2.400000	2.400000

Loss Tangent Analysis - DERIVATIVES:
Eglass/Epoxy (plain weave mat) at 10 kHz
Fiber type: Continuous fibers
Loss analysis based on AVE BOUNDS for Effective permittivity
Reference temperature: 28 [C]

No:	Vs:	Low D1:	High D1	Low D2	High D2
1	0.050000	0.936203	0.936994	0.064806	0.065830
2	0.100000	0.874326	0.875802	0.127532	0.129444
3	0.150000	0.814268	0.816329	0.188290	0.190961
4	0.200000	0.755935	0.758485	0.247186	0.250491
5	0.250000	0.699240	0.702188	0.304316	0.308136
6	0.300000	0.644102	0.647359	0.359774	0.363994
7	0.350000	0.590443	0.593924	0.413644	0.418155
8	0.400000	0.538192	0.541816	0.466006	0.470702
9	0.450000	0.487281	0.490969	0.516936	0.521715
10	0.500000	0.437647	0.441324	0.566504	0.571269
11	0.550000	0.389230	0.392825	0.614775	0.619432
12	0.600000	0.341975	0.345417	0.661812	0.666272
13	0.650000	0.295828	0.299050	0.707673	0.711848
14	0.700000	0.250740	0.253678	0.752413	0.756219
15	0.750000	0.206664	0.209255	0.796083	0.799441
16	0.800000	0.163556	0.165741	0.838733	0.841563

17	0.850000	0.121374	0.123094	0.880407	0.882636
18	0.900000	0.080079	0.081279	0.921149	0.922705
19	0.950000	0.039632	0.040258	0.961001	0.961812
20	1.000000	-0.000000	-0.000000	1.000000	1.000000

Frequency: 10000.000000 [Hz]
Fiber type: Continuous fibers
Loss analysis based on AVE BOUNDS for Effective permittivity
Reference temperature: 28 [C]

Matrix loss: 0.014400
Sphere loss: 0.003400

No:	Vs:	Vm:	Tan delta Bounds		Ave loss
1	0.050000	0.950000	0.013831	0.013845	0.013838
2	0.100000	0.900000	0.013267	0.013294	0.013280
3	0.150000	0.850000	0.012707	0.012745	0.012726
4	0.200000	0.800000	0.012151	0.012199	0.012175
5	0.250000	0.750000	0.011598	0.011654	0.011626
6	0.300000	0.700000	0.011048	0.011110	0.011079
7	0.350000	0.650000	0.010500	0.010568	0.010534
8	0.400000	0.600000	0.009954	0.010025	0.009990
9	0.450000	0.550000	0.009409	0.009483	0.009446
10	0.500000	0.500000	0.008866	0.008940	0.008903
11	0.550000	0.450000	0.008323	0.008397	0.008360
12	0.600000	0.400000	0.007780	0.007852	0.007816
13	0.650000	0.350000	0.007237	0.007305	0.007271
14	0.700000	0.300000	0.006694	0.006757	0.006725
15	0.750000	0.250000	0.006150	0.006206	0.006178
16	0.800000	0.200000	0.005604	0.005652	0.005628
17	0.850000	0.150000	0.005056	0.005095	0.005075
18	0.900000	0.100000	0.004507	0.004534	0.004520
19	0.950000	0.050000	0.003955	0.003969	0.003962
20	1.000000	0.000000	0.003400	0.003400	0.003400

End of Analysis for Eglass/Epoxy (plain weave mat) at 10 kHz

File run ID: Sun Nov 08 12:44:37 1998

Permittivity Analysis:
Eglass/Epoxy (plain weave mat) at 1 kHz
Fiber type: Continuos fibers
Reference temperature: 28 [C]

Ematrix: 3.290000
Efiber: 2.490000

No:	Vs:	Vm:	Elow:	Ehigh:	Eave:
0	0.000000	1.000000	3.290000	3.290000	3.290000
1	0.050000	0.950000	3.237984	3.250000	3.243992
2	0.100000	0.900000	3.187588	3.210000	3.198794
3	0.150000	0.850000	3.138736	3.170000	3.154368
4	0.200000	0.800000	3.091358	3.130000	3.110679
5	0.250000	0.750000	3.045390	3.090000	3.067695
6	0.300000	0.700000	3.000769	3.050000	3.025385
7	0.350000	0.650000	2.957437	3.010000	2.983718
8	0.400000	0.600000	2.915338	2.970000	2.942669
9	0.450000	0.550000	2.874421	2.930000	2.902211
10	0.500000	0.500000	2.834637	2.890000	2.862318
11	0.550000	0.450000	2.795939	2.850000	2.822969
12	0.600000	0.400000	2.758283	2.810000	2.784141
13	0.650000	0.350000	2.721628	2.770000	2.745814
14	0.700000	0.300000	2.685934	2.730000	2.707967
15	0.750000	0.250000	2.651165	2.690000	2.670583
16	0.800000	0.200000	2.617284	2.650000	2.633642
17	0.850000	0.150000	2.584259	2.610000	2.597129
18	0.900000	0.100000	2.552056	2.570000	2.561028
19	0.950000	0.050000	2.520646	2.530000	2.525323
20	1.000000	0.000000	2.490000	2.490000	2.490000

Loss Tangent Analysis - DERIVATIVES:
Eglass/Epoxy (plain weave mat) at 1 kHz
Fiber type: Continuous fibers
Loss analysis based on AVE BOUNDS for Effective permittivity
Reference temperature: 28 [C]

No:	Vs:	Low D1:	High D1	Low D2	High D2
1	0.050000	0.935040	0.935953	0.066148	0.067354
2	0.100000	0.872202	0.873906	0.129978	0.132228
3	0.150000	0.811369	0.813744	0.191626	0.194765
4	0.200000	0.752427	0.755363	0.251218	0.255098
5	0.250000	0.695274	0.698664	0.308871	0.313350
6	0.300000	0.639814	0.643555	0.364694	0.369637
7	0.350000	0.585956	0.589951	0.418788	0.424065
8	0.400000	0.533618	0.537772	0.471245	0.476733
9	0.450000	0.482720	0.486944	0.522155	0.527735
10	0.500000	0.433190	0.437397	0.571599	0.577157
11	0.550000	0.384960	0.389068	0.619653	0.625080
12	0.600000	0.337966	0.341895	0.666388	0.671580
13	0.650000	0.292146	0.295822	0.711871	0.716728
14	0.700000	0.247446	0.250795	0.756166	0.760590
15	0.750000	0.203813	0.206764	0.799329	0.803228

16	0.800000	0.161196	0.163682	0.841417	0.844702
17	0.850000	0.119549	0.121505	0.882481	0.885066
18	0.900000	0.078828	0.080191	0.922570	0.924371
19	0.950000	0.038991	0.039702	0.961728	0.962667
20	1.000000	0.000000	0.000000	1.000000	1.000000

Frequency: 1000.000000 [Hz]
Fiber type: Continuous fibers
Loss analysis based on AVE BOUNDS for Effective permittivity
Reference temperature: 28 [C]

Matrix loss: 0.008300
Sphere loss: 0.006000

No:	Vs:	Vm:	Tan delta Bounds		Ave loss
1	0.050000	0.950000	0.008176	0.008189	0.008182
2	0.100000	0.900000	0.008053	0.008078	0.008065
3	0.150000	0.850000	0.007932	0.007967	0.007949
4	0.200000	0.800000	0.007812	0.007856	0.007834
5	0.250000	0.750000	0.007693	0.007745	0.007719
6	0.300000	0.700000	0.007576	0.007634	0.007605
7	0.350000	0.650000	0.007460	0.007523	0.007491
8	0.400000	0.600000	0.007344	0.007411	0.007378
9	0.450000	0.550000	0.007230	0.007298	0.007264
10	0.500000	0.500000	0.007116	0.007185	0.007151
11	0.550000	0.450000	0.007003	0.007072	0.007037
12	0.600000	0.400000	0.006891	0.006957	0.006924
13	0.650000	0.350000	0.006779	0.006842	0.006810
14	0.700000	0.300000	0.006667	0.006725	0.006696
15	0.750000	0.250000	0.006556	0.006608	0.006582
16	0.800000	0.200000	0.006445	0.006489	0.006467
17	0.850000	0.150000	0.006333	0.006369	0.006351
18	0.900000	0.100000	0.006222	0.006247	0.006235
19	0.950000	0.050000	0.006111	0.006125	0.006118
20	1.000000	0.000000	0.006000	0.006000	0.006000

End of Analysis for Eglass/Epoxy (plain weave mat) at 1 kHz

File run ID: Sun Nov 08 12:38:15 1998

Permittivity Analysis:
Eglass/Epoxy (plain weave mat) system at 100 Hz
Fiber type: Continuous fibers
Reference temperature: 28 [C]

Ematrix: 3.320000
Efiber: 2.510000

No:	Vs:	Vm:	Elow:	Ehigh:	Eave:
0	0.000000	1.000000	3.320000	3.320000	3.320000
1	0.050000	0.950000	3.267281	3.279500	3.273390
2	0.100000	0.900000	3.216210	3.239000	3.227605
3	0.150000	0.850000	3.166711	3.198500	3.182606
4	0.200000	0.800000	3.118713	3.158000	3.138356
5	0.250000	0.750000	3.072147	3.117500	3.094824
6	0.300000	0.700000	3.026952	3.077000	3.051976
7	0.350000	0.650000	2.983068	3.036500	3.009784
8	0.400000	0.600000	2.940438	2.996000	2.968219
9	0.450000	0.550000	2.899009	2.955500	2.927254
10	0.500000	0.500000	2.858731	2.915000	2.886865
11	0.550000	0.450000	2.819557	2.874500	2.847028
12	0.600000	0.400000	2.781442	2.834000	2.807721
13	0.650000	0.350000	2.744344	2.793500	2.768922
14	0.700000	0.300000	2.708222	2.753000	2.730611
15	0.750000	0.250000	2.673039	2.712500	2.692770
16	0.800000	0.200000	2.638759	2.672000	2.655379
17	0.850000	0.150000	2.605346	2.631500	2.618423
18	0.900000	0.100000	2.572769	2.591000	2.581885
19	0.950000	0.050000	2.540997	2.550500	2.545749
20	1.000000	0.000000	2.510000	2.510000	2.510000

Loss Tangent Analysis - DERIVATIVES:
Eglass/Epoxy system at 100 Hz
Fiber type: Continuous fibers
Loss analysis based on AVE BOUNDS for Effective permittivity
Reference temperature: 28 [C]

No:	Vs:	Low D1:	High D1	Low D2	High D2
1	0.050000	0.934975	0.935895	0.066223	0.067440
2	0.100000	0.872084	0.873800	0.130115	0.132385
3	0.150000	0.811207	0.813601	0.191813	0.194979
4	0.200000	0.752232	0.755191	0.251444	0.255357
5	0.250000	0.695054	0.698469	0.309126	0.313643
6	0.300000	0.639576	0.643345	0.364969	0.369953
7	0.350000	0.585708	0.589732	0.419074	0.424396
8	0.400000	0.533365	0.537549	0.471536	0.477071
9	0.450000	0.482468	0.486722	0.522445	0.528071
10	0.500000	0.432945	0.437182	0.571881	0.577486
11	0.550000	0.384725	0.388862	0.619923	0.625395
12	0.600000	0.337745	0.341703	0.666641	0.671876
13	0.650000	0.291944	0.295645	0.712103	0.716999
14	0.700000	0.247266	0.250637	0.756373	0.760832

15	0.750000	0.203656	0.206628	0.799508	0.803438
16	0.800000	0.161067	0.163570	0.841565	0.844876
17	0.850000	0.119449	0.121418	0.882595	0.885200
18	0.900000	0.078759	0.080132	0.922648	0.924463
19	0.950000	0.038956	0.039672	0.961768	0.962715
20	1.000000	-0.000000	-0.000000	1.000000	1.000000

Frequency: 100.000000 [Hz]
Fiber type: Continuous fibers
Loss analysis based on AVE BOUNDS for Effective permittivity
Reference temperature: 28 [C]

Matrix loss: 0.005000
Sphere loss: 0.013500

No:	Vs:	Vm:	Tan delta Bounds		Ave loss
1	0.050000	0.950000	0.005427	0.005444	0.005436
2	0.100000	0.900000	0.005851	0.005884	0.005868
3	0.150000	0.850000	0.006273	0.006320	0.006296
4	0.200000	0.800000	0.006694	0.006752	0.006723
5	0.250000	0.750000	0.007113	0.007180	0.007147
6	0.300000	0.700000	0.007531	0.007607	0.007569
7	0.350000	0.650000	0.007948	0.008031	0.007989
8	0.400000	0.600000	0.008366	0.008452	0.008409
9	0.450000	0.550000	0.008784	0.008873	0.008828
10	0.500000	0.500000	0.009202	0.009292	0.009247
11	0.550000	0.450000	0.009621	0.009711	0.009666
12	0.600000	0.400000	0.010042	0.010129	0.010085
13	0.650000	0.350000	0.010465	0.010547	0.010506
14	0.700000	0.300000	0.010889	0.010965	0.010927
15	0.750000	0.250000	0.011316	0.011384	0.011350
16	0.800000	0.200000	0.011746	0.011804	0.011775
17	0.850000	0.150000	0.012179	0.012225	0.012202
18	0.900000	0.100000	0.012615	0.012648	0.012632
19	0.950000	0.050000	0.013056	0.013073	0.013064
20	1.000000	0.000000	0.013500	0.013500	0.013500

End of Analysis for Eglass/Epoxy system at 100 Hz

File run ID: Sun Nov 08 14:50:19 1998

Permittivity Analysis:
Matrix: 20%SF14 and 80% Epoxy FIBERS: E-glass plain weave mat at 100kHz
Fiber type: Continuos fibers
Reference temperature: 28 [C]

Ematrix: 3.020000
Efiber: 2.500000

No:	Vs:	Vm:	Elow:	Ehigh:	Eave:
0	0.000000	1.000000	3.020000	3.020000	3.020000
1	0.050000	0.950000	2.988915	2.994000	2.991458
2	0.100000	0.900000	2.958464	2.968000	2.963232
3	0.150000	0.850000	2.928627	2.942000	2.935313
4	0.200000	0.800000	2.899386	2.916000	2.907693
5	0.250000	0.750000	2.870722	2.890000	2.880361
6	0.300000	0.700000	2.842620	2.864000	2.853310
7	0.350000	0.650000	2.815063	2.838000	2.826532
8	0.400000	0.600000	2.788035	2.812000	2.800018
9	0.450000	0.550000	2.761522	2.786000	2.773761
10	0.500000	0.500000	2.735507	2.760000	2.747754
11	0.550000	0.450000	2.709978	2.734000	2.721989
12	0.600000	0.400000	2.684922	2.708000	2.696461
13	0.650000	0.350000	2.660324	2.682000	2.671162
14	0.700000	0.300000	2.636173	2.656000	2.646087
15	0.750000	0.250000	2.612457	2.630000	2.621228
16	0.800000	0.200000	2.589163	2.604000	2.596582
17	0.850000	0.150000	2.566281	2.578000	2.572141
18	0.900000	0.100000	2.543801	2.552000	2.547900
19	0.950000	0.050000	2.521710	2.526000	2.523855
20	1.000000	0.000000	2.500000	2.500000	2.500000

Loss Tangent Analysis - DERIVATIVES:
Matrix: 20%SF14 and 80% Epoxy FIBERS: E-glass plain weave mat at 100kHz
Fiber type: Continuos fibers
Loss analysis based on AVE BOUNDS for Effective permittivity
Reference temperature: 28 [C]

No:	Vs:	Low D1:	High D1	Low D2	High D2
1	0.050000	0.940247	0.940668	0.060256	0.060765
2	0.100000	0.881755	0.882544	0.119179	0.120133
3	0.150000	0.824477	0.825584	0.176820	0.178157
4	0.200000	0.768368	0.769744	0.233227	0.234888
5	0.250000	0.713386	0.714982	0.288447	0.290374
6	0.300000	0.659489	0.661259	0.342523	0.344661
7	0.350000	0.606639	0.608538	0.395499	0.397792
8	0.400000	0.554799	0.556783	0.447413	0.449810
9	0.450000	0.503933	0.505960	0.498305	0.500753
10	0.500000	0.454008	0.456035	0.548211	0.550660
11	0.550000	0.404990	0.406979	0.597165	0.599567
12	0.600000	0.356850	0.358760	0.645202	0.647510
13	0.650000	0.309557	0.311351	0.692353	0.694520
14	0.700000	0.263083	0.264724	0.738648	0.740630
15	0.750000	0.217401	0.218853	0.784116	0.785871

16	0.800000	0.172485	0.173714	0.828787	0.830270
17	0.850000	0.128311	0.129281	0.872685	0.873857
18	0.900000	0.084853	0.085532	0.915837	0.916657
19	0.950000	0.042090	0.042446	0.958268	0.958697
20	1.000000	0.000000	0.000000	1.000000	1.000000

Frequency: 100000.000000 [Hz]
Fiber type: Continuos fibers
Loss analysis based on AVE BOUNDS for Effective permittivity
Reference temperature: 28 [C]

Matrix loss: 0.020900
Sphere loss: 0.005000

No:	Vs:	Vm:	Tan delta Bounds		Ave loss
1	0.050000	0.950000	0.020090	0.020101	0.020096
2	0.100000	0.900000	0.019284	0.019305	0.019295
3	0.150000	0.850000	0.018482	0.018511	0.018496
4	0.200000	0.800000	0.017682	0.017719	0.017700
5	0.250000	0.750000	0.016884	0.016928	0.016906
6	0.300000	0.700000	0.016089	0.016138	0.016113
7	0.350000	0.650000	0.015296	0.015348	0.015322
8	0.400000	0.600000	0.014504	0.014559	0.014531
9	0.450000	0.550000	0.013713	0.013770	0.013741
10	0.500000	0.500000	0.012923	0.012981	0.012952
11	0.550000	0.450000	0.012133	0.012190	0.012162
12	0.600000	0.400000	0.011344	0.011399	0.011372
13	0.650000	0.350000	0.010555	0.010607	0.010581
14	0.700000	0.300000	0.009765	0.009813	0.009789
15	0.750000	0.250000	0.008974	0.009018	0.008996
16	0.800000	0.200000	0.008183	0.008220	0.008201
17	0.850000	0.150000	0.007390	0.007419	0.007404
18	0.900000	0.100000	0.006595	0.006616	0.006606
19	0.950000	0.050000	0.005799	0.005810	0.005804
20	1.000000	0.000000	0.005000	0.005000	0.005000

End of Analysis for Matrix: 20%SF14 and 80% Epoxy FIBERS: E-glass plain weave mat at 100kHz

File run ID: Sun Nov 08 14:42:40 1998

Permittivity Analysis:
MATRIX: 20%SF14 and 80% Epoxy FIBERS: E-glass plain weave at 10 kHz
Fiber type: Continuous fibers
Reference temperature: 28 [C]

Ematrix: 2.900000
Efiber: 2.400000

No:	Vs:	Vm:	Elow:	Ehigh:	Eave:
0	0.000000	1.000000	2.900000	2.900000	2.900000
1	0.050000	0.950000	2.870103	2.875000	2.872552
2	0.100000	0.900000	2.840816	2.850000	2.845408
3	0.150000	0.850000	2.812121	2.825000	2.818561
4	0.200000	0.800000	2.784000	2.800000	2.792000
5	0.250000	0.750000	2.756436	2.775000	2.765718
6	0.300000	0.700000	2.729412	2.750000	2.739706
7	0.350000	0.650000	2.702913	2.725000	2.713956
8	0.400000	0.600000	2.676923	2.700000	2.688462
9	0.450000	0.550000	2.651429	2.675000	2.663214
10	0.500000	0.500000	2.626415	2.650000	2.638208
11	0.550000	0.450000	2.601869	2.625000	2.613435
12	0.600000	0.400000	2.577778	2.600000	2.588889
13	0.650000	0.350000	2.554128	2.575000	2.564564
14	0.700000	0.300000	2.530909	2.550000	2.540455
15	0.750000	0.250000	2.508108	2.525000	2.516554
16	0.800000	0.200000	2.485714	2.500000	2.492857
17	0.850000	0.150000	2.463717	2.475000	2.469358
18	0.900000	0.100000	2.442105	2.450000	2.446053
19	0.950000	0.050000	2.420870	2.425000	2.422935
20	1.000000	0.000000	2.400000	2.400000	2.400000

Loss Tangent Analysis - DERIVATIVES:
MATRIX: 20%SF14 and 80% Epoxy FIBERS: E-glass plain weave at 10 kHz
Fiber type: Continuos fibers
Loss analysis based on AVE BOUNDS for Effective permittivity
Reference temperature: 28 [C]

No:	Vs:	Low D1:	High D1	Low D2	High D2
1	0.050000	0.940231	0.940654	0.060273	0.060784
2	0.100000	0.881726	0.882518	0.119211	0.120167
3	0.150000	0.824438	0.825548	0.176863	0.178205
4	0.200000	0.768320	0.769699	0.233280	0.234947
5	0.250000	0.713331	0.714931	0.288507	0.290441
6	0.300000	0.659429	0.661204	0.342589	0.344734
7	0.350000	0.606576	0.608480	0.395569	0.397869
8	0.400000	0.554734	0.556723	0.447485	0.449889
9	0.450000	0.503867	0.505899	0.498378	0.500833
10	0.500000	0.453943	0.455976	0.548282	0.550739
11	0.550000	0.404927	0.406921	0.597234	0.599644
12	0.600000	0.356790	0.358706	0.645267	0.647582
13	0.650000	0.309502	0.311301	0.692413	0.694587
14	0.700000	0.263033	0.264679	0.738702	0.740691

15	0.750000	0.217358	0.218814	0.784164	0.785924
16	0.800000	0.172449	0.173681	0.828827	0.830315
17	0.850000	0.128282	0.129255	0.872716	0.873891
18	0.900000	0.084834	0.085514	0.915859	0.916681
19	0.950000	0.042080	0.042436	0.958279	0.958709
20	1.000000	-0.000000	-0.000000	1.000000	1.000000

Frequency: 10000.000000 [Hz]
Fiber type: Continuous fibers
Loss analysis based on AVE BOUNDS for Effective permittivity
Reference temperature: 28 [C]

Matrix loss: 0.016000
Sphere loss: 0.003000

No:	Vs:	Vm:	Tan delta Bounds		Ave loss
1	0.050000	0.950000	0.015339	0.015347	0.015343
2	0.100000	0.900000	0.014680	0.014695	0.014688
3	0.150000	0.850000	0.014024	0.014046	0.014035
4	0.200000	0.800000	0.013370	0.013397	0.013384
5	0.250000	0.750000	0.012719	0.012750	0.012734
6	0.300000	0.700000	0.012069	0.012104	0.012086
7	0.350000	0.650000	0.011420	0.011459	0.011439
8	0.400000	0.600000	0.010773	0.010813	0.010793
9	0.450000	0.550000	0.010126	0.010168	0.010147
10	0.500000	0.500000	0.009480	0.009523	0.009501
11	0.550000	0.450000	0.008835	0.008877	0.008856
12	0.600000	0.400000	0.008189	0.008230	0.008210
13	0.650000	0.350000	0.007544	0.007582	0.007563
14	0.700000	0.300000	0.006898	0.006933	0.006916
15	0.750000	0.250000	0.006251	0.006283	0.006267
16	0.800000	0.200000	0.005604	0.005631	0.005617
17	0.850000	0.150000	0.004955	0.004977	0.004966
18	0.900000	0.100000	0.004305	0.004320	0.004313
19	0.950000	0.050000	0.003653	0.003662	0.003658
20	1.000000	0.000000	0.003000	0.003000	0.003000

End of Analysis for MATRIX: 20%SF14 and 80% Epoxy FIBERS: E-glass plain weave at 10 kHz

File run ID: Sun Nov 08 14:39:47 1998

Permittivity Analysis:
MATRIX: 20%SF14 and 80%Epoxy FIBERS:E-glass plain weave at 1Khz
Fiber type: Continuous fibers
Reference temperature: 28 [C]

Ematrix: 3.110000
Efiber: 2.490000

No:	Vs:	Vm:	Elow:	Ehigh:	Eave:
0	0.000000	1.000000	3.110000	3.110000	3.110000
1	0.050000	0.950000	3.071757	3.079000	3.075379
2	0.100000	0.900000	3.034444	3.048000	3.041222
3	0.150000	0.850000	2.998026	3.017000	3.007513
4	0.200000	0.800000	2.962471	2.986000	2.974236
5	0.250000	0.750000	2.927750	2.955000	2.941375
6	0.300000	0.700000	2.893834	2.924000	2.908917
7	0.350000	0.650000	2.860694	2.893000	2.876847
8	0.400000	0.600000	2.828305	2.862000	2.845153
9	0.450000	0.550000	2.796641	2.831000	2.813821
10	0.500000	0.500000	2.765679	2.800000	2.782839
11	0.550000	0.450000	2.735394	2.769000	2.752197
12	0.600000	0.400000	2.705765	2.738000	2.721883
13	0.650000	0.350000	2.676772	2.707000	2.691886
14	0.700000	0.300000	2.648393	2.676000	2.662196
15	0.750000	0.250000	2.620609	2.645000	2.632805
16	0.800000	0.200000	2.593403	2.614000	2.603701
17	0.850000	0.150000	2.566755	2.583000	2.574878
18	0.900000	0.100000	2.540650	2.552000	2.546325
19	0.950000	0.050000	2.515070	2.521000	2.518035
20	1.000000	0.000000	2.490000	2.490000	2.490000

Loss Tangent Analysis - DERIVATIVES:
MATRIX: 20%SF14 and 80%Epoxy FIBERS:E-glass plain weave at 1Khz
Fiber type: Continuous fibers
Loss analysis based on AVE BOUNDS for Effective permittivity
Reference temperature: 28 [C]

No:	Vs:	Low D1:	High D1	Low D2	High D2
1	0.050000	0.938354	0.938936	0.062364	0.063091
2	0.100000	0.878268	0.879357	0.123060	0.124422
3	0.150000	0.819672	0.821197	0.182165	0.184070
4	0.200000	0.762501	0.764392	0.239750	0.242112
5	0.250000	0.706693	0.708884	0.295883	0.298618
6	0.300000	0.652191	0.654616	0.350627	0.353656
7	0.350000	0.598939	0.601535	0.404045	0.407288
8	0.400000	0.546884	0.549593	0.456192	0.459575
9	0.450000	0.495979	0.498741	0.507123	0.510573
10	0.500000	0.446175	0.448934	0.556889	0.560335
11	0.550000	0.397429	0.400130	0.605539	0.608913
12	0.600000	0.349698	0.352289	0.653118	0.656354
13	0.650000	0.302942	0.305372	0.699670	0.702705
14	0.700000	0.257124	0.259343	0.745236	0.748008

15	0.750000	0.212208	0.214168	0.789856	0.792305
16	0.800000	0.168158	0.169814	0.833567	0.835635
17	0.850000	0.124943	0.126249	0.876403	0.878034
18	0.900000	0.082531	0.083443	0.918400	0.919540
19	0.950000	0.040893	0.041369	0.959589	0.960184
20	1.000000	0.000000	0.000000	1.000000	1.000000

Frequency: 1000.000000 [Hz]
Fiber type: Continuous fibers
Loss analysis based on AVE BOUNDS for Effective permittivity
Reference temperature: 28 [C]

Matrix loss: 0.019200
Sphere loss: 0.006000

No:	Vs:	Vm:	Tan delta Bounds		Ave loss
1	0.050000	0.950000	0.018522	0.018537	0.018530
2	0.100000	0.900000	0.017849	0.017877	0.017863
3	0.150000	0.850000	0.017179	0.017219	0.017199
4	0.200000	0.800000	0.016513	0.016562	0.016537
5	0.250000	0.750000	0.015849	0.015908	0.015878
6	0.300000	0.700000	0.015188	0.015254	0.015221
7	0.350000	0.650000	0.014530	0.014601	0.014565
8	0.400000	0.600000	0.013873	0.013948	0.013910
9	0.450000	0.550000	0.013218	0.013295	0.013256
10	0.500000	0.500000	0.012563	0.012641	0.012602
11	0.550000	0.450000	0.011910	0.011987	0.011948
12	0.600000	0.400000	0.011256	0.011331	0.011294
13	0.650000	0.350000	0.010603	0.010674	0.010638
14	0.700000	0.300000	0.009949	0.010015	0.009982
15	0.750000	0.250000	0.009295	0.009353	0.009324
16	0.800000	0.200000	0.008639	0.008689	0.008664
17	0.850000	0.150000	0.007983	0.008022	0.008002
18	0.900000	0.100000	0.007324	0.007352	0.007338
19	0.950000	0.050000	0.006663	0.006678	0.006671
20	1.000000	0.000000	0.006000	0.006000	0.006000

End of Analysis for MATRIX: 20%SF14 and 80%Epoxy FIBERS:E-glass plain weave at 1Khz

File run ID: Sun Nov 08 14:39:47 1998

Permittivity Analysis:
MATRIX: 20%SF14 and 80%Epoxy FIBERS:E-glass plain weave at 1Khz
Fiber type: Continuous fibers
Reference temperature: 28 [C]

Ematrix: 3.110000
Efiber: 2.490000

No:	Vs:	Vm:	Elow:	Ehigh:	Eave:
0	0.000000	1.000000	3.110000	3.110000	3.110000
1	0.050000	0.950000	3.071757	3.079000	3.075379
2	0.100000	0.900000	3.034444	3.048000	3.041222
3	0.150000	0.850000	2.998026	3.017000	3.007513
4	0.200000	0.800000	2.962471	2.986000	2.974236
5	0.250000	0.750000	2.927750	2.955000	2.941375
6	0.300000	0.700000	2.893834	2.924000	2.908917
7	0.350000	0.650000	2.860694	2.893000	2.876847
8	0.400000	0.600000	2.828305	2.862000	2.845153
9	0.450000	0.550000	2.796641	2.831000	2.813821
10	0.500000	0.500000	2.765679	2.800000	2.782839
11	0.550000	0.450000	2.735394	2.769000	2.752197
12	0.600000	0.400000	2.705765	2.738000	2.721883
13	0.650000	0.350000	2.676772	2.707000	2.691886
14	0.700000	0.300000	2.648393	2.676000	2.662196
15	0.750000	0.250000	2.620609	2.645000	2.632805
16	0.800000	0.200000	2.593403	2.614000	2.603701
17	0.850000	0.150000	2.566755	2.583000	2.574878
18	0.900000	0.100000	2.540650	2.552000	2.546325
19	0.950000	0.050000	2.515070	2.521000	2.518035
20	1.000000	0.000000	2.490000	2.490000	2.490000

Loss Tangent Analysis - DERIVATIVES:
MATRIX: 20%SF14 and 80%Epoxy FIBERS:E-glass plain weave at 1Khz
Fiber type: Continuos fibers
Loss analysis based on AVE BOUNDS for Effective permittivity
Reference temperature: 28 [C]

No:	Vs:	Low D1:	High D1	Low D2	High D2
1	0.050000	0.938354	0.938936	0.062364	0.063091
2	0.100000	0.878268	0.879357	0.123060	0.124422
3	0.150000	0.819672	0.821197	0.182165	0.184070
4	0.200000	0.762501	0.764392	0.239750	0.242112
5	0.250000	0.706693	0.708884	0.295883	0.298618
6	0.300000	0.652191	0.654616	0.350627	0.353656
7	0.350000	0.598939	0.601535	0.404045	0.407288
8	0.400000	0.546884	0.549593	0.456192	0.459575
9	0.450000	0.495979	0.498741	0.507123	0.510573
10	0.500000	0.446175	0.448934	0.556889	0.560335
11	0.550000	0.397429	0.400130	0.605539	0.608913
12	0.600000	0.349698	0.352289	0.653118	0.656354
13	0.650000	0.302942	0.305372	0.699670	0.702705
14	0.700000	0.257124	0.259343	0.745236	0.748008

15	0.750000	0.212208	0.214168	0.789856	0.792305
16	0.800000	0.168158	0.169814	0.833567	0.835635
17	0.850000	0.124943	0.126249	0.876403	0.878034
18	0.900000	0.082531	0.083443	0.918400	0.919540
19	0.950000	0.040893	0.041369	0.959589	0.960184
20	1.000000	0.000000	0.000000	1.000000	1.000000

Frequency: 1000.000000 [Hz]
Fiber type: Continuous fibers
Loss analysis based on AVE BOUNDS for Effective permittivity
Reference temperature: 28 [C]

Matrix loss: 0.019200
Sphere loss: 0.006000

No:	Vs:	Vm:	Tan delta Bounds		Ave loss
1	0.050000	0.950000	0.018522	0.018537	0.018530
2	0.100000	0.900000	0.017849	0.017877	0.017863
3	0.150000	0.850000	0.017179	0.017219	0.017199
4	0.200000	0.800000	0.016513	0.016562	0.016537
5	0.250000	0.750000	0.015849	0.015908	0.015878
6	0.300000	0.700000	0.015188	0.015254	0.015221
7	0.350000	0.650000	0.014530	0.014601	0.014565
8	0.400000	0.600000	0.013873	0.013948	0.013910
9	0.450000	0.550000	0.013218	0.013295	0.013256
10	0.500000	0.500000	0.012563	0.012641	0.012602
11	0.550000	0.450000	0.011910	0.011987	0.011948
12	0.600000	0.400000	0.011256	0.011331	0.011294
13	0.650000	0.350000	0.010603	0.010674	0.010638
14	0.700000	0.300000	0.009949	0.010015	0.009982
15	0.750000	0.250000	0.009295	0.009353	0.009324
16	0.800000	0.200000	0.008639	0.008689	0.008664
17	0.850000	0.150000	0.007983	0.008022	0.008002
18	0.900000	0.100000	0.007324	0.007352	0.007338
19	0.950000	0.050000	0.006663	0.006678	0.006671
20	1.000000	0.000000	0.006000	0.006000	0.006000

End of Analysis for MATRIX: 20%SF14 and 80%Epoxy FIBERS:E-glass plain weave at 1Khz

File run ID: Sun Nov 08 14:29:58 1998

Permittivity Analysis:
MATRIX: 20%SF14 and 80%Epoxy FIBERS: E-glass plain weave at 100Hz
Fiber type: Continuous fibers
Reference temperature: 28 [C]

Ematrix: 3.230000
Efiber: 2.510000

No:	Vs:	Vm:	Elow:	Ehigh:	Eave:
0	0.000000	1.000000	3.230000	3.230000	3.230000
1	0.050000	0.950000	3.184328	3.194000	3.189164
2	0.100000	0.900000	3.139930	3.158000	3.148965
3	0.150000	0.850000	3.096753	3.122000	3.109377
4	0.200000	0.800000	3.054748	3.086000	3.070374
5	0.250000	0.750000	3.013866	3.050000	3.031933
6	0.300000	0.700000	2.974065	3.014000	2.994032
7	0.350000	0.650000	2.935301	2.978000	2.956650
8	0.400000	0.600000	2.897534	2.942000	2.919767
9	0.450000	0.550000	2.860727	2.906000	2.883363
10	0.500000	0.500000	2.824843	2.870000	2.847422
11	0.550000	0.450000	2.789849	2.834000	2.811924
12	0.600000	0.400000	2.755710	2.798000	2.776855
13	0.650000	0.350000	2.722398	2.762000	2.742199
14	0.700000	0.300000	2.689881	2.726000	2.707940
15	0.750000	0.250000	2.658131	2.690000	2.674066
16	0.800000	0.200000	2.627122	2.654000	2.640561
17	0.850000	0.150000	2.596829	2.618000	2.607414
18	0.900000	0.100000	2.567226	2.582000	2.574613
19	0.950000	0.050000	2.538291	2.546000	2.542145
20	1.000000	0.000000	2.510000	2.510000	2.510000

Loss Tangent Analysis - DERIVATIVES:
Matrix: 20%SF14 and 80%Epoxy FIBERS: E-glass plain weave
Fiber type: Continuous fibers
Loss analysis based on AVE BOUNDS for Effective permittivity
Reference temperature: 28 [C]

No:	Vs:	Low D1:	High D1	Low D2	High D2
1	0.050000	0.936615	0.937363	0.064335	0.065298
2	0.100000	0.875078	0.876477	0.126671	0.128471
3	0.150000	0.815297	0.817251	0.187114	0.189629
4	0.200000	0.757183	0.759602	0.245761	0.248874
5	0.250000	0.700654	0.703450	0.302704	0.306303
6	0.300000	0.645633	0.648724	0.358030	0.362007
7	0.350000	0.592048	0.595353	0.411817	0.416070
8	0.400000	0.539831	0.543272	0.464142	0.468571
9	0.450000	0.488918	0.492422	0.515076	0.519585
10	0.500000	0.439249	0.442744	0.564685	0.569182
11	0.550000	0.390768	0.394185	0.613031	0.617428
12	0.600000	0.343421	0.346694	0.660173	0.664385
13	0.650000	0.297158	0.300223	0.706167	0.710111
14	0.700000	0.251931	0.254727	0.751065	0.754662
15	0.750000	0.207697	0.210163	0.794915	0.798090

16	0.800000	0.164412	0.166492	0.837765	0.840442
17	0.850000	0.122037	0.123675	0.879659	0.881767
18	0.900000	0.080533	0.081677	0.920636	0.922108
19	0.950000	0.039866	0.040462	0.960738	0.961506
20	1.000000	-0.000000	-0.000000	1.000000	1.000000

Frequency: 100.000000 [Hz]
Fiber type: Continuous fibers
Loss analysis based on AVE BOUNDS for Effective permittivity
Reference temperature: 28 [C]

Matrix loss: 0.035400
Sphere loss: 0.014000

No:	Vs:	Vm:	Tan delta Bounds		Ave loss
1	0.050000	0.950000	0.034290	0.034327	0.034308
2	0.100000	0.900000	0.033188	0.033259	0.033224
3	0.150000	0.850000	0.032096	0.032196	0.032146
4	0.200000	0.800000	0.031010	0.031136	0.031073
5	0.250000	0.750000	0.029932	0.030079	0.030005
6	0.300000	0.700000	0.028859	0.029024	0.028941
7	0.350000	0.650000	0.027791	0.027969	0.027880
8	0.400000	0.600000	0.026727	0.026915	0.026821
9	0.450000	0.550000	0.025666	0.025860	0.025763
10	0.500000	0.500000	0.024607	0.024803	0.024705
11	0.550000	0.450000	0.023551	0.023745	0.023648
12	0.600000	0.400000	0.022495	0.022683	0.022589
13	0.650000	0.350000	0.021440	0.021618	0.021529
14	0.700000	0.300000	0.020384	0.020549	0.020466
15	0.750000	0.250000	0.019327	0.019474	0.019401
16	0.800000	0.200000	0.018268	0.018394	0.018331
17	0.850000	0.150000	0.017207	0.017307	0.017257
18	0.900000	0.100000	0.016142	0.016213	0.016177
19	0.950000	0.050000	0.015073	0.015111	0.015092
20	1.000000	0.000000	0.014000	0.014000	0.014000

End of Analysis for Matrix: 20%SF14 and 80%Epoxy FIBERS: E-glass plain weave

File run ID: Sun Nov 08 16:22:19 1998

Permittivity Analysis:
MATRIX: 40%SF14 and 60% Epoxy FIBERS: E-glass plain weave mat at 100 kHz
Fiber type: Continuous fibers
Reference temperature: 28 [C]

Ematrix: 2.850000
Efiber: 2.500000

No:	Vs:	Vm:	Elow:	Ehigh:	Eave:
0	0.000000	1.000000	2.850000	2.850000	2.850000
1	0.050000	0.950000	2.830189	2.832500	2.831344
2	0.100000	0.900000	2.810651	2.815000	2.812825
3	0.150000	0.850000	2.791381	2.797500	2.794440
4	0.200000	0.800000	2.772374	2.780000	2.776187
5	0.250000	0.750000	2.753623	2.762500	2.758062
6	0.300000	0.700000	2.735125	2.745000	2.740062
7	0.350000	0.650000	2.716873	2.727500	2.722187
8	0.400000	0.600000	2.698864	2.710000	2.704432
9	0.450000	0.550000	2.681091	2.692500	2.686796
10	0.500000	0.500000	2.663551	2.675000	2.669276
11	0.550000	0.450000	2.646240	2.657500	2.651870
12	0.600000	0.400000	2.629151	2.640000	2.634576
13	0.650000	0.350000	2.612282	2.622500	2.617391
14	0.700000	0.300000	2.595628	2.605000	2.600314
15	0.750000	0.250000	2.579186	2.587500	2.583343
16	0.800000	0.200000	2.562950	2.570000	2.566475
17	0.850000	0.150000	2.546917	2.552500	2.549708
18	0.900000	0.100000	2.531083	2.535000	2.533042
19	0.950000	0.050000	2.515446	2.517500	2.516473
20	1.000000	0.000000	2.500000	2.500000	2.500000

Loss Tangent Analysis - DERIVATIVES:
MATRIX: 40%SF14 and 60% Epoxy FIBERS: E-glass plain weave mat at 100 kHz
Fiber type: Continuos fibers
Loss analysis based on AVE BOUNDS for Effective permittivity
Reference temperature: 28 [C]

No:	Vs:	Low D1:	High D1	Low D2	High D2
1	0.050000	0.943408	0.943610	0.056822	0.057053
2	0.100000	0.887617	0.887998	0.112812	0.113247
3	0.150000	0.832607	0.833144	0.167992	0.168604
4	0.200000	0.778358	0.779027	0.222383	0.223146
5	0.250000	0.724852	0.725631	0.276006	0.276893
6	0.300000	0.672069	0.672936	0.328878	0.329866
7	0.350000	0.619992	0.620924	0.381021	0.382083
8	0.400000	0.568604	0.569581	0.432451	0.433565
9	0.450000	0.517887	0.518887	0.483187	0.484328
10	0.500000	0.467825	0.468829	0.533245	0.534390
11	0.550000	0.418402	0.419390	0.582643	0.583769
12	0.600000	0.369604	0.370556	0.631397	0.632482
13	0.650000	0.321415	0.322312	0.679521	0.680543
14	0.700000	0.273822	0.274644	0.727032	0.727969

15	0.750000	0.226809	0.227538	0.773944	0.774775
16	0.800000	0.180363	0.180982	0.820271	0.820976
17	0.850000	0.134472	0.134962	0.866027	0.866585
18	0.900000	0.089123	0.089467	0.911225	0.911616
19	0.950000	0.044303	0.044483	0.955878	0.956084
20	1.000000	0.000000	0.000000	1.000000	1.000000

Frequency: 100000.000000 [Hz]
Fiber type: Continuous fibers
Loss analysis based on AVE BOUNDS for Effective permittivity
Reference temperature: 28 [C]

Matrix loss: 0.020500
Sphere loss: 0.005000

No:	Vs:	Vm:	Tan delta Bounds		Ave loss
1	0.050000	0.950000	0.019718	0.019723	0.019721
2	0.100000	0.900000	0.018938	0.018948	0.018943
3	0.150000	0.850000	0.018159	0.018173	0.018166
4	0.200000	0.800000	0.017382	0.017399	0.017391
5	0.250000	0.750000	0.016606	0.016626	0.016616
6	0.300000	0.700000	0.015831	0.015854	0.015842
7	0.350000	0.650000	0.015056	0.015081	0.015069
8	0.400000	0.600000	0.014283	0.014309	0.014296
9	0.450000	0.550000	0.013510	0.013537	0.013523
10	0.500000	0.500000	0.012737	0.012764	0.012751
11	0.550000	0.450000	0.011964	0.011992	0.011978
12	0.600000	0.400000	0.011192	0.011218	0.011205
13	0.650000	0.350000	0.010420	0.010445	0.010432
14	0.700000	0.300000	0.009647	0.009670	0.009659
15	0.750000	0.250000	0.008874	0.008895	0.008885
16	0.800000	0.200000	0.008101	0.008119	0.008110
17	0.850000	0.150000	0.007327	0.007341	0.007334
18	0.900000	0.100000	0.006552	0.006562	0.006557
19	0.950000	0.050000	0.005777	0.005782	0.005779
20	1.000000	0.000000	0.005000	0.005000	0.005000

End of Analysis for MATRIX: 40%SF14 and 60% Epoxy FIBERS: E-glass plain weave mat at 100 kHz

File run ID: Sun Nov 08 16:20:19 1998

Permittivity Analysis:
MATRIX: 40%SF14 and 60% Epoxy with E-glass plain weave at 10 kHz
Fiber type: Continuous fibers
Reference temperature: 28 [C]

Ematrix: 2.700000
Efiber: 2.400000

No:	Vs:	Vm:	Elow:	Ehigh:	Eave:
0	0.000000	1.000000	2.700000	2.700000	2.700000
1	0.050000	0.950000	2.683230	2.685000	2.684115
2	0.100000	0.900000	2.666667	2.670000	2.668333
3	0.150000	0.850000	2.650307	2.655000	2.652653
4	0.200000	0.800000	2.634146	2.640000	2.637073
5	0.250000	0.750000	2.618182	2.625000	2.621591
6	0.300000	0.700000	2.602410	2.610000	2.606205
7	0.350000	0.650000	2.586826	2.595000	2.590913
8	0.400000	0.600000	2.571429	2.580000	2.575714
9	0.450000	0.550000	2.556213	2.565000	2.560607
10	0.500000	0.500000	2.541176	2.550000	2.545588
11	0.550000	0.450000	2.526316	2.535000	2.530658
12	0.600000	0.400000	2.511628	2.520000	2.515814
13	0.650000	0.350000	2.497110	2.505000	2.501055
14	0.700000	0.300000	2.482759	2.490000	2.486379
15	0.750000	0.250000	2.468571	2.475000	2.471786
16	0.800000	0.200000	2.454545	2.460000	2.457273
17	0.850000	0.150000	2.440678	2.445000	2.442839
18	0.900000	0.100000	2.426966	2.430000	2.428483
19	0.950000	0.050000	2.413408	2.415000	2.414204
20	1.000000	0.000000	2.400000	2.400000	2.400000

Loss Tangent Analysis - DERIVATIVES:
MATRIX: 40%SF14 and 60% Epoxy with E-glass plain weave at 10 kHz
Fiber type: Continuous fibers
Loss analysis based on AVE BOUNDS for Effective permittivity
Reference temperature: 28 [C]

No:	Vs:	Low D1:	High D1	Low D2	High D2
1	0.050000	0.944109	0.944272	0.056075	0.056259
2	0.100000	0.888923	0.889232	0.111420	0.111767
3	0.150000	0.834428	0.834862	0.166052	0.166541
4	0.200000	0.780607	0.781149	0.219988	0.220598
5	0.250000	0.727445	0.728076	0.273244	0.273954
6	0.300000	0.674927	0.675630	0.325835	0.326625
7	0.350000	0.623040	0.623797	0.377776	0.378627
8	0.400000	0.571769	0.572562	0.429082	0.429974
9	0.450000	0.521100	0.521914	0.479767	0.480682
10	0.500000	0.471021	0.471838	0.529844	0.530763
11	0.550000	0.421518	0.422322	0.579328	0.580233
12	0.600000	0.372580	0.373355	0.628231	0.629104
13	0.650000	0.324194	0.324924	0.676567	0.677389
14	0.700000	0.276348	0.277018	0.724346	0.725100
15	0.750000	0.229031	0.229626	0.771582	0.772251

16	0.800000	0.182231	0.182736	0.818285	0.818853
17	0.850000	0.135939	0.136339	0.864468	0.864918
18	0.900000	0.090143	0.090424	0.910141	0.910457
19	0.950000	0.044834	0.044981	0.955315	0.955481
20	1.000000	-0.000000	-0.000000	1.000000	1.000000

Frequency: 10000.000000 [Hz]
Fiber type: Continuous fibers
Loss analysis based on AVE BOUNDS for Effective permittivity
Reference temperature: 28 [C]

Matrix loss: 0.017800
Sphere loss: 0.003000

No:	Vs:	Vm:	Tan delta Bounds		Ave loss
1	0.050000	0.950000	0.017055	0.017058	0.017057
2	0.100000	0.900000	0.016311	0.016318	0.016315
3	0.150000	0.850000	0.015569	0.015578	0.015573
4	0.200000	0.800000	0.014827	0.014839	0.014833
5	0.250000	0.750000	0.014086	0.014100	0.014093
6	0.300000	0.700000	0.013346	0.013361	0.013354
7	0.350000	0.650000	0.012607	0.012623	0.012615
8	0.400000	0.600000	0.011868	0.011885	0.011877
9	0.450000	0.550000	0.011130	0.011147	0.011138
10	0.500000	0.500000	0.010391	0.010409	0.010400
11	0.550000	0.450000	0.009653	0.009671	0.009662
12	0.600000	0.400000	0.008915	0.008933	0.008924
13	0.650000	0.350000	0.008177	0.008194	0.008186
14	0.700000	0.300000	0.007439	0.007454	0.007447
15	0.750000	0.250000	0.006701	0.006714	0.006707
16	0.800000	0.200000	0.005962	0.005973	0.005968
17	0.850000	0.150000	0.005222	0.005232	0.005227
18	0.900000	0.100000	0.004482	0.004489	0.004486
19	0.950000	0.050000	0.003742	0.003745	0.003743
20	1.000000	0.000000	0.003000	0.003000	0.003000

End of Analysis for MATRIX: 40%SF14 and 60% Epoxy with E-glass plain weave at 10 kHz

File run ID: Sun Nov 08 16:17:01 1998

Permittivity Analysis:
40%SF14 and 60% Epoxy FIBERS: E-glass plain weave at 1kHz
Fiber type: Continuous fibers
Reference temperature: 28 [C]

Ematrix: 2.940000
Efiber: 2.490000

No:	Vs:	Vm:	Elow:	Ehigh:	Eave:
0	0.000000	1.000000	2.940000	2.940000	2.940000
1	0.050000	0.950000	2.913672	2.917500	2.915586
2	0.100000	0.900000	2.887811	2.895000	2.891405
3	0.150000	0.850000	2.862405	2.872500	2.867452
4	0.200000	0.800000	2.837442	2.850000	2.843721
5	0.250000	0.750000	2.812911	2.827500	2.820205
6	0.300000	0.700000	2.788800	2.805000	2.796900
7	0.350000	0.650000	2.765099	2.782500	2.773800
8	0.400000	0.600000	2.741798	2.760000	2.750899
9	0.450000	0.550000	2.718886	2.737500	2.728193
10	0.500000	0.500000	2.696354	2.715000	2.705677
11	0.550000	0.450000	2.674192	2.692500	2.683346
12	0.600000	0.400000	2.652391	2.670000	2.661196
13	0.650000	0.350000	2.630943	2.647500	2.639222
14	0.700000	0.300000	2.609840	2.625000	2.617420
15	0.750000	0.250000	2.589072	2.602500	2.595786
16	0.800000	0.200000	2.568632	2.580000	2.574316
17	0.850000	0.150000	2.548512	2.557500	2.553006
18	0.900000	0.100000	2.528705	2.535000	2.531852
19	0.950000	0.050000	2.509203	2.512500	2.510852
20	1.000000	0.000000	2.490000	2.490000	2.490000

Loss Tangent Analysis - DERIVATIVES:
40%SF14 and 60% Epoxy FIBERS: E-glass plain weave at 1kHz
Fiber type: Continuous fibers
Loss analysis based on AVE BOUNDS for Effective permittivity
Reference temperature: 28 [C]

No:	Vs:	Low D1:	High D1	Low D2	High D2
1	0.050000	0.941512	0.941837	0.058869	0.059254
2	0.100000	0.884095	0.884706	0.116614	0.117336
3	0.150000	0.827714	0.828572	0.173273	0.174286
4	0.200000	0.772336	0.773404	0.228880	0.230141
5	0.250000	0.717930	0.719170	0.283472	0.284937
6	0.300000	0.664463	0.665840	0.337080	0.338707
7	0.350000	0.611907	0.613386	0.389737	0.391484
8	0.400000	0.560232	0.561780	0.441472	0.443300
9	0.450000	0.509413	0.510996	0.492315	0.494184
10	0.500000	0.459422	0.461008	0.542295	0.544167
11	0.550000	0.410235	0.411791	0.591437	0.593275
12	0.600000	0.361827	0.363324	0.639768	0.641536
13	0.650000	0.314174	0.315582	0.687313	0.688975
14	0.700000	0.267256	0.268545	0.734095	0.735617

15	0.750000	0.221050	0.222191	0.780138	0.781486
16	0.800000	0.175535	0.176501	0.825463	0.826604
17	0.850000	0.130691	0.131455	0.870091	0.870994
18	0.900000	0.086500	0.087035	0.914044	0.914676
19	0.950000	0.042942	0.043222	0.957341	0.957672
20	1.000000	0.000000	0.000000	1.000000	1.000000

Frequency: 1000.000000 [Hz]
Fiber type: Continuous fibers
Loss analysis based on AVE BOUNDS for Effective permittivity
Reference temperature: 28 [C]

Matrix loss: 0.030500
Sphere loss: 0.006000

No:	Vs:	Vm:	Tan delta Bounds		Ave loss
1	0.050000	0.950000	0.029258	0.029270	0.029264
2	0.100000	0.900000	0.028021	0.028043	0.028032
3	0.150000	0.850000	0.026787	0.026819	0.026803
4	0.200000	0.800000	0.025556	0.025597	0.025576
5	0.250000	0.750000	0.024329	0.024376	0.024352
6	0.300000	0.700000	0.023104	0.023156	0.023130
7	0.350000	0.650000	0.021881	0.021938	0.021909
8	0.400000	0.600000	0.020659	0.020720	0.020689
9	0.450000	0.550000	0.019439	0.019502	0.019470
10	0.500000	0.500000	0.018220	0.018283	0.018252
11	0.550000	0.450000	0.017002	0.017064	0.017033
12	0.600000	0.400000	0.015784	0.015844	0.015814
13	0.650000	0.350000	0.014565	0.014622	0.014594
14	0.700000	0.300000	0.013346	0.013399	0.013372
15	0.750000	0.250000	0.012126	0.012173	0.012150
16	0.800000	0.200000	0.010905	0.010945	0.010925
17	0.850000	0.150000	0.009682	0.009714	0.009698
18	0.900000	0.100000	0.008457	0.008480	0.008468
19	0.950000	0.050000	0.007230	0.007242	0.007236
20	1.000000	0.000000	0.006000	0.006000	0.006000

End of Analysis for 40%SF14 and 60% Epoxy FIBERS: E-glass plain weave at 1kHz

File run ID: Sun Nov 08 16:14:11 1998

Permittivity Analysis:
40%SF14 and 60% Epoxy FIBERS: E-glass plain weave at 100 Hz
Fiber type: Continuous fibers
Reference temperature: 28 [C]

Ematrix: 3.130000
Efiber: 2.510000

No:	Vs:	Vm:	Elow:	Ehigh:	Eave:
0	0.000000	1.000000	3.130000	3.130000	3.130000
1	0.050000	0.950000	3.091814	3.099000	3.095407
2	0.100000	0.900000	3.054549	3.068000	3.061274
3	0.150000	0.850000	3.018171	3.037000	3.027586
4	0.200000	0.800000	2.982650	3.006000	2.994325
5	0.250000	0.750000	2.947955	2.975000	2.961477
6	0.300000	0.700000	2.914058	2.944000	2.929029
7	0.350000	0.650000	2.880931	2.913000	2.896966
8	0.400000	0.600000	2.848550	2.882000	2.865275
9	0.450000	0.550000	2.816888	2.851000	2.833944
10	0.500000	0.500000	2.785922	2.820000	2.802961
11	0.550000	0.450000	2.755630	2.789000	2.772315
12	0.600000	0.400000	2.725989	2.758000	2.741994
13	0.650000	0.350000	2.696979	2.727000	2.711990
14	0.700000	0.300000	2.668580	2.696000	2.682290
15	0.750000	0.250000	2.640773	2.665000	2.652887
16	0.800000	0.200000	2.613540	2.634000	2.623770
17	0.850000	0.150000	2.586862	2.603000	2.594931
18	0.900000	0.100000	2.560724	2.572000	2.566362
19	0.950000	0.050000	2.535108	2.541000	2.538054
20	1.000000	0.000000	2.510000	2.510000	2.510000

Loss Tangent Analysis - DERIVATIVES:
40%SF14 and 60% Epoxy FIBERS: E-glass plain weave at 100 Hz
Fiber type: Continuous fibers
Loss analysis based on AVE BOUNDS for Effective permittivity
Reference temperature: 28 [C]

No:	Vs:	Low D1:	High D1	Low D2	High D2
1	0.050000	0.938445	0.939019	0.062262	0.062977
2	0.100000	0.878436	0.879510	0.122872	0.124212
3	0.150000	0.819902	0.821406	0.181906	0.183781
4	0.200000	0.762782	0.764647	0.239434	0.241760
5	0.250000	0.707013	0.709173	0.295524	0.298218
6	0.300000	0.652539	0.654931	0.350237	0.353220
7	0.350000	0.599305	0.601867	0.403634	0.406829
8	0.400000	0.547261	0.549932	0.455771	0.459103
9	0.450000	0.496356	0.499081	0.506701	0.510099
10	0.500000	0.446546	0.449268	0.556475	0.559869
11	0.550000	0.397786	0.400452	0.605140	0.608464
12	0.600000	0.350035	0.352592	0.652742	0.655930
13	0.650000	0.303254	0.305652	0.699323	0.702313
14	0.700000	0.257404	0.259594	0.744924	0.747655
15	0.750000	0.212451	0.214386	0.789585	0.791998
16	0.800000	0.168361	0.169995	0.833341	0.835379

17	0.850000	0.125100	0.126389	0.876228	0.877836
18	0.900000	0.082639	0.083540	0.918280	0.919403
19	0.950000	0.040948	0.041419	0.959527	0.960114
20	1.000000	-0.000000	-0.000000	1.000000	1.000000

Frequency: 100.000000 [Hz]
Fiber type: Continuous fibers
Loss analysis based on AVE BOUNDS for Effective permittivity
Reference temperature: 28 [C]

Matrix loss: 0.066400
Sphere loss: 0.014000

No:	Vs:	Vm:	Tan delta Bounds		Ave loss
1	0.050000	0.950000	0.063716	0.063763	0.063739
2	0.100000	0.900000	0.061048	0.061136	0.061092
3	0.150000	0.850000	0.058394	0.058519	0.058457
4	0.200000	0.800000	0.055754	0.055910	0.055832
5	0.250000	0.750000	0.053124	0.053307	0.053215
6	0.300000	0.700000	0.050503	0.050709	0.050606
7	0.350000	0.650000	0.047891	0.048113	0.048002
8	0.400000	0.600000	0.045285	0.045520	0.045402
9	0.450000	0.550000	0.042684	0.042926	0.042805
10	0.500000	0.500000	0.040087	0.040331	0.040209
11	0.550000	0.450000	0.037491	0.037733	0.037612
12	0.600000	0.400000	0.034896	0.035131	0.035014
13	0.650000	0.350000	0.032301	0.032524	0.032412
14	0.700000	0.300000	0.029704	0.029909	0.029806
15	0.750000	0.250000	0.027103	0.027286	0.027194
16	0.800000	0.200000	0.024497	0.024654	0.024575
17	0.850000	0.150000	0.021885	0.022010	0.021948
18	0.900000	0.100000	0.019266	0.019354	0.019310
19	0.950000	0.050000	0.016638	0.016685	0.016661
20	1.000000	0.000000	0.014000	0.014000	0.014000

End of Analysis for 40%SF14 and 60% Epoxy FIBERS: E-glass plain weave at 100 Hz