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Dielectric Polymer Actuators' Overall Performance Affected by a Large Range of Filler Materials, Each with a Unique Cross Section

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ABSTRACT

Electroactive polymers may be broken down into many core subtypes that can be differentiated from one another. These subtypes include piezo polymers, dynamic elastomers, and electrical resistivity polymers. Electroactive polymers that have a fast response time and are suitable for most actuator applications are these sorts of polymers. Dielectric elastomers polymers are the most astounding of the three materials that have been researched so far. The microstructure of a composite material has a direct impact on the overall properties of the material. Regardless of whether this influence is beneficial or bad, it has an impact. This will give us a better understanding of how these parameters contribute to the total dielectric constant of the material. For example, we want to know how each of these components influences the overall dielectric constant. Cylinders with circular cross-sections, as well as linear dielectric behaviour are assumed for filler particles in this study. In order to keep things simple, we'll assume these two things. Random and periodic microstructures are taken into consideration in this specific study As an example of a periodic microstructure, a square or hexagonal arrangement of cylindrical fibres may be taken into consideration. Nanocomposites having inclusions with very high dielectric constants have been proven in experiments to achieve an extremely high overall dielectric constant at volume fractions of less than 11%. Because the dielectric constant of the inclusions is quite low, this is conceivable.

Keywords: *Dielectric Material; Dielectric Elastomers; Nanocomposites; Dielectric Constants; EAPs*

1.0 Introduction

Electroactive polymers, often known as EAPs, are materials that alter their structure when exposed to electric fields, as seen in Figure 1. Furthermore, they are perfect for the design of sensors and actuators in a broad variety of applications.

It is more easier and less costly to manufacture complex surfaces and geometries using EAP-based actuators than it is with traditional actuation systems. Pneumatics, hydraulics, piezoelectric ceramics, solenoids, voice coils, and pneumatics are all traditional actuation methods. Actuators based on EAPs, on the other hand, may easily adapt to surfaces that have a distorted geometry. [7] For a long period of time, their usage was restricted because of their high working voltage. Artificial muscles, miniature robots modelled after biological systems (such as insects), and biomedical equipment, such as for the treatment of cancer, might all benefit from the employment of these actuators. [8] Our theoretical knowledge of EAP composites is still quite limited even though many experiments have been carried out to define their behaviour. Modelling the electromechanical response of EAP composites as a function of their microstructure is critical for the efficient design of EAP actuators, hence the majority of our efforts will be devoted to creating these models.

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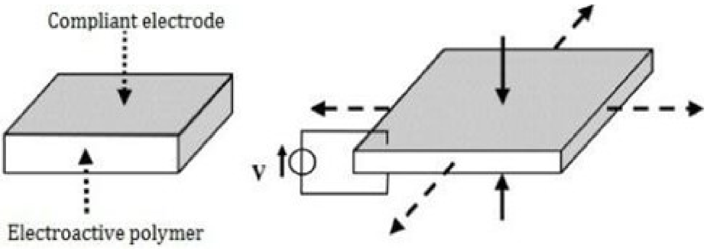
Figure 1: Electroactive Polymer Deforms Under Force Right, Off Strains Surpass 100%



In electrostiff polymers, a Coulomb contact between the charges on the electrodes coated on the specimen might result in electromechanical coupling (Maxwell stress effect). Materials that exhibit electromechanical coupling are called piezoelectric polymers because of the torque applied to molecular dipoles by an electric field. An electromechanical coupling is observed in synthetic rubbers, also called dielectric elastomers, when Coulomb forces interact between charges on electrodes adhered to a test specimen. We'll be spending much of our attention and effort on electroactive polymers and dielectric elastomers since these materials have the best performance characteristics. First, we'll go through the details of the second and third EAPs. Polyurethane (PU) and VDF-TrFE-CFE (VDF-TrFE) composites will receive a large amount of attention [10].

Dielectric elastomers and electrostrictive polymers have been the primary focus of the vast majority of experimental and theoretical research on EAPs. This is because of the better performance characteristics that dielectric elastomers and electrostrictive polymers possess. [11][12][13][14] Table 1 contains a number of the most effective dielectric and electrostrictive polymers, such as PUs and silicones, as well as the most effective natural muscles and the most advanced piezoelectric ceramics, such as PZT polycrystals and PZN-PT single crystals. Table 1 also contains a number of the most advanced piezoelectric ceramics, such as PZT polycrystals and PZN-PT single crystals. This table also includes a variety of additional helpful materials, such as electrostrictive and dielectric materials, among others (PZN-PT). When doing an analysis of actuator materials, some of the parameters that are taken into consideration include the maximum strain and stress that the material is capable of withstanding. If the actuator materials' operating voltages were excessively high, the range of feasible applications for these materials would be severely constrained (from tens of KVs to MVs). As a result, the electric field that was present at the time when the maximum performance was measured is also taken into consideration as an actuator parameter (this information is displayed in the seventh column of the table). [15] [16] Last but not least, it is essential to emphasise the significance of the temperature dependence of the performance parameters, as well as the fact that the results presented in Table 1 were determined using testing conducted at room temperature (25 degrees Celsius).

The following is a list of the specific objectives that should be accomplished via the application of this effort.

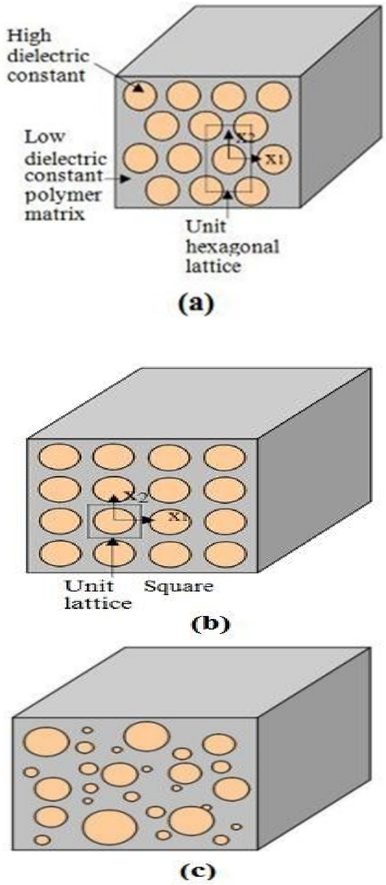
2.0 Performance of Various Actuators Materials

The data in Table 1 [8, 17], [18], [19], and [10] can be used to draw conclusions regarding a wide range of important issues. PZTs, a kind of piezoelectric ceramic, can generate considerable pressures even in the presence of extremely low electric fields thanks to its exceptionally high coupling efficiency (more than fifty percent). The fact that PZTs are the most common type of piezoelectric ceramics isn't enough to explain this (less than five volts per millimetre). The deformations they can cause, on the other hand, aren't life-threatening (the highest strain that can be achieved is less than 0.2 percent). On the other hand, the properties of relaxor PT single crystals, such as PZN-8 per cent, are far more favourable. The ferroelectric hysterisis losses in these crystals are greatly decreased due to their behaviour. Indeed, the difference between PZTs and PZN-PTs is about comparable to an order of magnitude when it comes to the maximum strain and energy density that can be achieved. As opposed to this, the manufacture of PZN-PT single crystals is infamously difficult, making them an ideal material for high-performance electrical devices. For example, polyurethane (PU) and silicones, which are dielectric elastomers, are able to undergo large deformations (up to a strain of 40 percent) while still maintaining high energy densities and coupling efficiencies, but piezoelectric ceramics cannot. By virtue of its elastic characteristics, the dielectric elastomer allows this. On the other hand, the maximum pressure that can be applied by dielectric elastomers is just a few megapascals (on the order of one megapascal), and the working electric field is fairly high (around one hundred fifty volts per micrometre). Silicones, an intriguing type of material, have been shown to exhibit properties that are eerily similar to those exhibited by human muscle. P(VDF-TrFE-CFE) is the electrostrictive polymer that has the greatest performance characteristics among P(VDF-TrFE) based electrostrictive polymers based on Poly(vinylidene flouride-trifluoro ethylene). Not only is it able to generate very high stresses (on the order of 50 MPa), but it can also sustain considerable deformations in the same manner as piezoelectric ceramics and dielectric elastomers. This ability allows it to be used in a variety of engineering applications (with strains to the tune of 5 percent). In addition to this, they are capable of attaining huge energy densities and working with high coupling efficiencies. These are two of their other distinguishing characteristics. However, similar to dielectric elastomers, these materials suffer from the issue of having a very high working electric field (more than 100V/m). Surprisingly, this restriction in electrostrictive polymers and dielectric elastomers may be easily avoided through the construction of composites of actuator materials with high dielectric constant organic nano-fillers. A significant advancement in nanotechnology was responsible for making this new development conceivable. For example, the dielectric constant of an elastomeric system can be increased from seven to one thousand by manufacturing a nanocomposite of polyurethane (PU) that contains three and a half percent by volume of copper pthalocyanine. This will result in the system having a higher dielectric constant (CuPc). Because of this, the working electric field may be decreased from 160 V/m to 11.5 V/m as a direct result of this.

3.0 Modelling

In this group include materials such as PUs, silicones, and P(VDF-TrFE-CFEs) [20]. The electromechanical coupling qualities of EAPs are quite strong. Due to their low dielectric constants, polymers inherently need huge electric fields in order to provide an acceptable actuation pressure or stroke. Polymers, by their very nature, have low dielectric constants, which explains this. Incorporating nanofillers with high dielectric constants can easily minimise the operational electric field that is present in these materials. This is a straightforward approach to achieving your objective. There is an increase in the average dielectric constant when high dielectric constant nanofillers are used, however this also produces a drop in the composite's effective dielectric strength due to an inhomogeneous electric field with local hot spots. The reason for this is because the nanofillers have a greater dielectric constant than the composite. If the breakdown strength of the nanocomposite technique is reduced, the method will suffer a substantial deficit in terms of its ability to conduct electricity. In other words, as the electric field increases, so does the rate at which electric energy density drops. Since dielectric constant and dielectric strength are seemingly in conflict, the primary problem is to develop composite microstructures that can strike a balance between the two. It’s going to be difficult, to say the least. Two distinct types of beginning microstructures, also known as initial distributions of phases, are considered in these investigations, as shown in Figures 2(a), 2(b), and 2(c): periodic and random (c). Analysis of two-phase microstructures for the existence of periodic and random elliptical inclusions is conducted. These microstructural variables are elliptoids, ellipsoids of various sizes and shapes (e.g., spheres of various sizes and shapes, cylinders of various sizes and shapes, lamellae of various sizes and shapes), and lattices. This is a critical topic that has to be made clear since it’s so important. In order to determine the volume percentage, average form, and distribution of inclusions.

Figure 2: (a) Hexagonal Periodic Fibre Polymers. 100 Percent Fiber-To-Matrix. Dash-Shaped Unit Cells. 2 (b) Square-Fiber Composite. 2(c) Random Cylindrical



4.0 Effective Behaviour of Dielectric Composites

The organic fillers that are frequently utilised in the creation of dielectric composites have mechanical properties that are equivalent to those of the matrix polymers. This is because dielectric composites are made up of organic materials. As a direct consequence of this, the major purpose of this research will be to explore the effective dielectric properties of dielectric and (a, y) a, (a, y) a, and (x, a) (0y) composites in respect to the original microstructure.. The implications of making this assumption are as follows:

This is due to the fact that both effective dielectric constants and dielectric strength tensors are representations of dielectric strengths in the form of tensors. It is essential to keep in mind that the effective dielectric constant and dielectric strength of a composite can still be anisotropic due to the anisotropic distribution of the phases within the composite, even if the phases of the composite itself are isotropic. This is the case even if the phases of the composite themselves are isotropic (for example, laminated or fibre reinforced composites). Throughout the entirety of this research project, a substantial amount of emphasis will be placed on the analysis of practically important isotropic and transversely isotropic dielectric composites with spherical and cylindrical hexagonal arrangements of unidirectional fibres. It is not difficult to demonstrate that the effective dielectric constant tensor Keff is related to the average electric field for the choice of reference axes that are depicted in Fig. Fig. 3(a) and Fig. 3(b). At get to the composite's average electric flux density, D=0KeffEin, the equation looks like this: Regarding the selection of reference axes that are displayed in Fig. Fig. 3(a) and Fig. 3

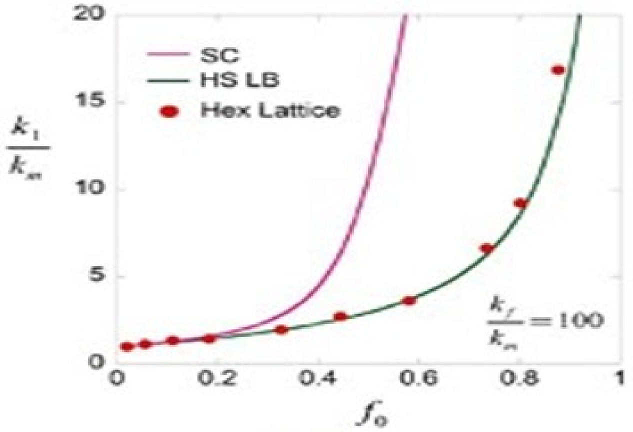
One may compute the effective in-plane dielectric constant simply by figuring out how much flux density is generated by an electric field applied in the x-direction. Finding a solution to the problem of calculating the average flux density produced by the electric field should accomplish this. In order to obtain the effective in-plane dielectric constant, we must first solve this specific problem. A constant potential boundary condition would be established at the composite's outside edge. If the electric field is uniform and E11=1 is its value, this condition is compatible. As a result, the electric field distribution around the composite fibres will be uniform. There will be a uniform distribution of electrical fields in and around each of the fibres since this criteria has been implemented. This is owing to the fact that the representative volume element of a composite is often assumed to be made up of a high number of inclusions, and as a result of this condition, this will be the case. For another reason, this is because it is assumed that a composite's representative volume element is composed mostly of inclusions. Before calculating the effective in-plane dielectric constant, one must first solve for the electric flux density distribution at close proximity to the border of the territory In conclusion, when one takes into account the fact that the electric flux density field would be the same from one phase to the next for electric fields that are aligned with the fibre direction, the effective dielectric constant along the fibres becomes.

In this equation, c0 stands for the volume percent of the fibre (filler), The breakdown of the dielectric properties of the composite material is brought on by the formation of localised zones inside the material that extend from one electrode to the other and in which the electric (stress) field is equivalent to the dielectric strength of the local phase. These zones move from one electrode to the other as they go through the circuit. Because of this, the effective dielectric strength is going to be a function not only of the distribution of phases and the dielectric characteristics of the phases, but also of the direction of the applied electric field in relation to the microstructure. In other words, the effective dielectric strength is going to be a function of both the distribution of phases and the dielectric characteristics of the phases.

Each phase on its own, in addition to the matrix phase and the filler phase). It is presumed that the relation between the electric flux density D and the electric field E= - varies with each of the phases and has the form. This is because the form describes how the relation should behave. It is essential to keep in mind that the phase behaviours used in this context are comparable to the elastic-perfectly plastic interactions observed in the plasticity of metals (where the yield stress plays the same role as the dielectric strength over here). Analyses of periodic composites are to be computed utilising the commercial software package ABAQUS in conjunction with user material models for modelling the elastic-perfectly plastic type response of dielectric materials. These analyses are to be carried out with the intention of producing accurate results. On the other hand, analyses of random composites can be carried out utilising approximation approaches of the Mori-Tanaka type.

5.0 Result and Discussion

In this specific piece of study, we are exclusively focused in polymer composites that contain inclusions in the form of fibres. It is hypothesised that the dielectric constant of the fibres is one hundred times higher than that of the matrix. The effective in-plane and out-of-plane dielectric constants k1, and k3, respectively, are determined as a function of the volume fraction of the fibres f0. The purpose of this study is to analyse the effects that microstructure has on effective dielectric constant and to find out what happens when we reach the percolation limit in order to better understand what happens.



(d)

The total in-plane dielectric constant k1 is displayed in Fig. 2(d) and Fig. 2(e), respectively, as a function of the volume % of the fibres in both hexagonal and square lattices. Additionally included in the picture are the effective in-plane dielectric constants for random composites. The values of these constants are shown here in the form of a function of the volume % of the fibres. It is essential to keep in mind that the effective dielectric constant for periodic composites sees a significant increase at the percolation volume %, which, for a square arrangement of fibres, is equal to / 4, and for a hexagonal arrangement of fibres, is 0.907. In addition, the Hashin Shtrikhman lower limit (HS LB) for the in-plane dielectric constant of transversely isotropic microstructures is in great agreement with the FEM predictions established for hexagonal lattices. These predictions were made using the finite element method. At lower volume fractions, or volume fractions that are considerably smaller than the percolation limits, it is abundantly clear that random and periodic microstructures give identical estimates for the effective in-plane dielectric constant. This is the case because the percolation limits are reached at volume fractions that are significantly larger than the percolation limits. This is the situation due to the fact that the percolation limitations are a lot lower than the volume fractions that are being considered here.

Figure 2d is a representation of the effective in-plane dielectric constant for periodic composites with hexagonal lattice topologies. This constant is represented as a function of the fibre volume percent. Estimates for random composites using the Hashin-Shtrikhman lower bound (HS LB) and the self-consistent methodology are also reported in this work. Both of these methods were developed by the authors of the current research (SC). 2. e) The effective in-plane dielectric constant for periodic composites with square lattice topologies; this constant is shown here as a function of the fibre volume percent. In this section, estimates for random composites are also presented in accordance with the Hashin Shtrikhman lower limit (HS LB) and the self-consistent approach.

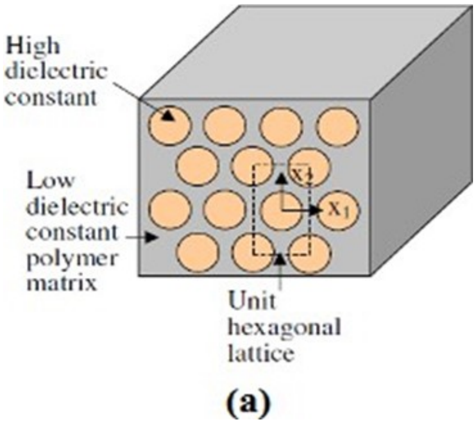
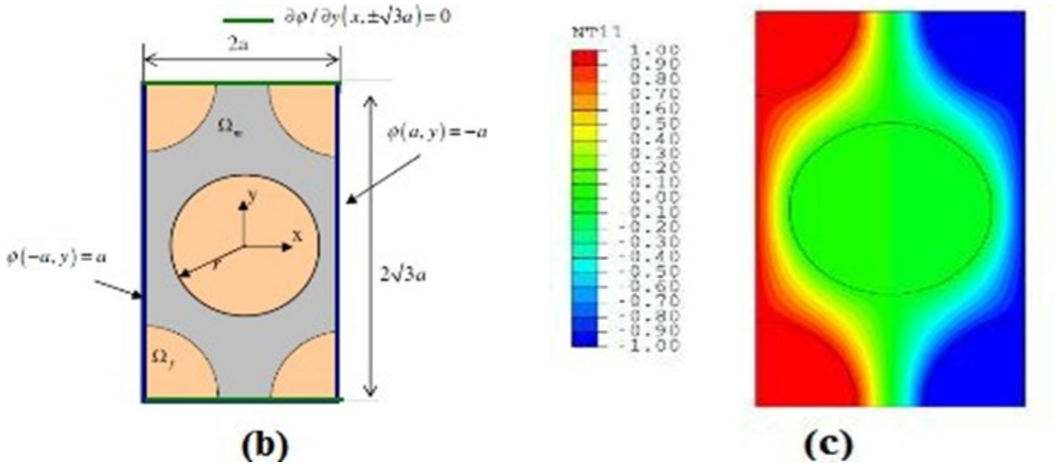
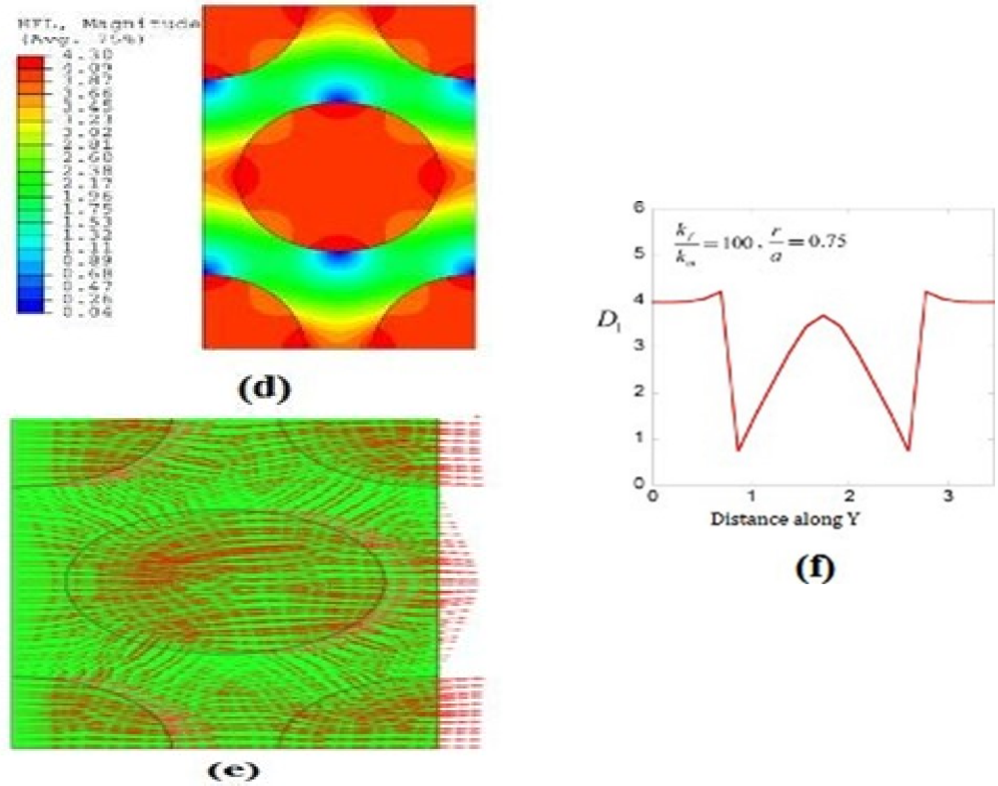


Figure 3: (a) Polymer Composite with Hexagonal Fibre Inclusions. The Fibre and Matrix Dielectric Constants are 100-to-1. 3(b) Unit Hexagonal Lattice Cell in FEM Investigations. Potential Energy



The finite element studies for a hexagonal arrangement of fibres are presented in Fig. 3(a) and 3(b) (b). In this case, the fibre radius was 0.75 times the lattice parameter a = 1, as illustrated. The effective dielectric constant may be determined by placing constant potentials on the left and right sides of the unit cell. This has the same value (which add up to a unit electric field in the horizontal direction). Flux boundary conditions on the top and bottom sides of the unit cell must be set to zero, and the average flux density via the left face must be determined. The effective dielectric constant is the ratio of the average electric flux density through the left face to the electric permittivity of vacuum. This conclusion was reached after determining that the effective dielectric constant was equal to the ratio. Because of this result, we may deduce that the effective dielectric constant is 1, as stated in the previous sentence. To put it another way, the effective in-plane permittivity would be equal to the average flux density that would be flowing through the left face of the material. This is another method of expressing the same idea. Figure 3a and 3b illustrate the hexagonal arrangement of the fibres, the structure of the unit cell, and the boundary conditions that were applied to the material (b). Figures 3(c), 3(d), and 3(e), respectively, show the electric potential and electric flux density profiles for the imposed boundary conditions. Figure 3(c) shows the electric potential profile. It should come as no surprise that the electric flux density is channelled, for the most part, via the fibres that have a high dielectric constant. This is readily obvious. The data shown in Fig. 3 helps to illustrate the significance of these findings (f). To calculate the effective dielectric constant, just take the mean value of the electric flux density shown in Figure 3f. This will give you the value you need.



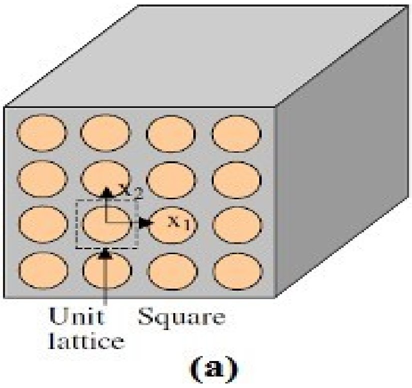
(d)

(e)

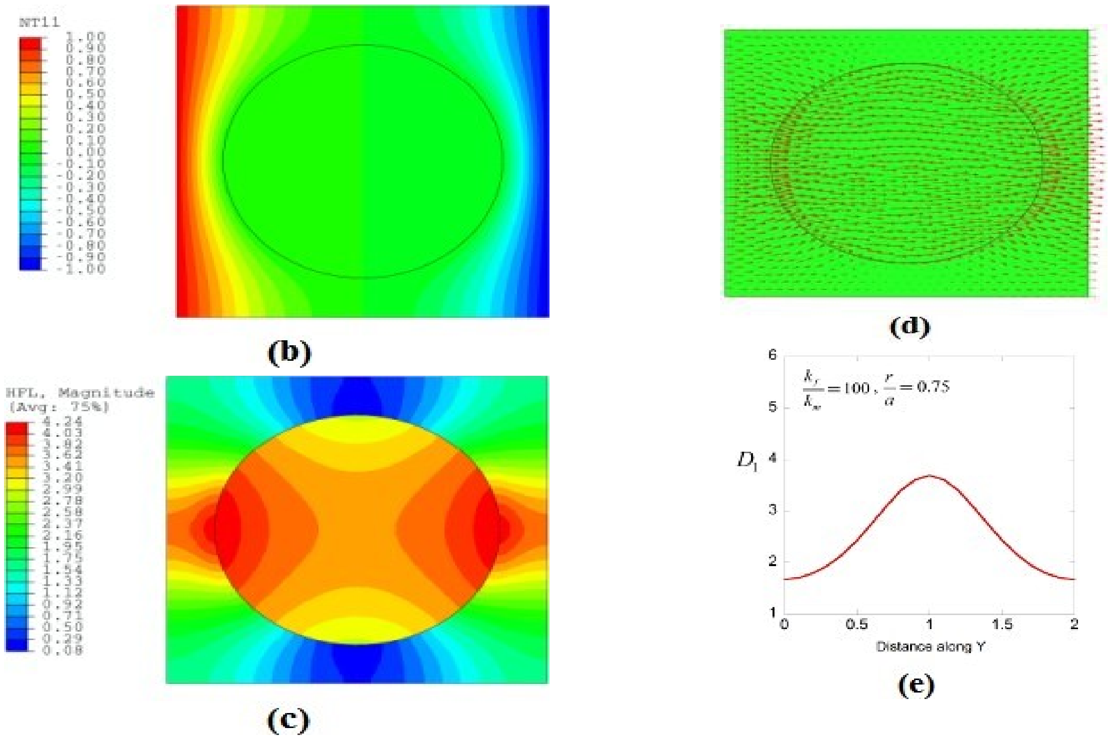
(f)

The electric potential profile that is present all the way through the unit lattice can be seen in Fig. 3c. This profile is present when there is an average electric field that is equal to one in the horizontal direction. 3(d) Resultant electric flux density profile. (e) The flow patterns and the density of the electric flux. (f) The electric flux density in the vertical direction along the left face of the unit lattice when the third position is occupied The value that is customary for it would be identical to the one that is used for the plane direction constant when it is in use.

The results that are shown in Figure 4(a), Figure 4(b), Figure 4(c), and Figure 4(e) are analogous to those that are displayed in Figure 3, with the exception that they are for a square arrangement of fibres. It is possible to demonstrate that the electric potential profiles as well as the electric flux density profiles are significantly different between the two circumstances. In spite of this, it can not be denied that the vast bulk of the electric flux passes through the fibres. This is true regardless of the context, including the current one.



A overview of the observations is shown in Figure 5, which includes both random and periodic microstructures (square and hexagonal layouts, respectively). The effective dielectric constants, both in-plane and out-of-plane, are shown here as a function of the volume % of the fibres, and the findings are reported for each. It is essential to bear in mind that the value of the out-of-plane dielectric constant does not vary with the kind of microstructure. When electric fields are applied in the direction of the fibre, they have the effect of decoupling the fields that are contained inside the fibres and those that are contained within the polymer matrix.



There are high dielectric constant fibre inclusions that are arranged in square patterns in the polymer composite of interest as seen in Figure 4. (a). Fibre dielectric constants have been assumed to be precisely 100 times greater than matrix dielectric constants. As is customary, we begin our FEM analyses with a value of 1. In the horizontal axis, the average electric field is equal to one and stretches from the end of the unit lattice to the other. Step 4 displays the resulting electric flux density profiles (c). Electric flux density on the left face of unit lattice at the fourth position in the vertical direction. 4(d) The patterns of flux density movement. If you were to compute the average value of the constant that is effective in the plane direction, you would get the same result.

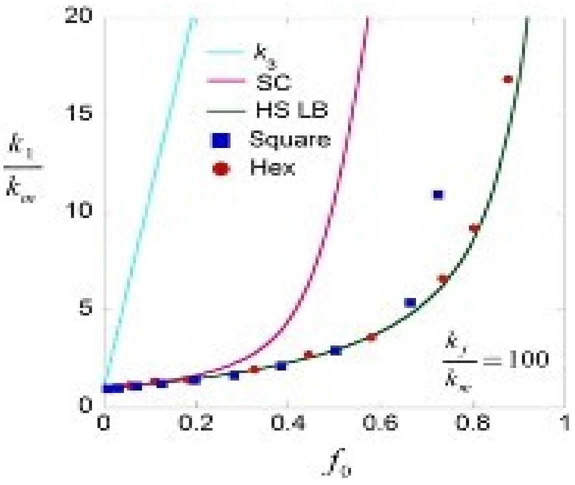


Figure 5 displays the effective in-plane and out-of-plane dielectric constants, k1 and k3, as a function of volume fraction for periodic microstructures with square and hexagonal lattice arrangements. It also displays estimates for random composites using the Hashin Shtrikhman lower bound (HS LB) method and the self-consistent (SC) method.

6.0 Conclusion

Polymer composites have an effective dielectric constant that is substantially greater than the matrix polymer's dielectric constant when charge injection effects are absent or minor. Even if the matrix polymer has a high dielectric constant, this is the case. Matrix polymers, on the other hand, tend to be less dense than polymer composites, which are more dense. In order for this to occur, the percolation volume % of the composite must be greater than the matrix polymer percentage. That's not going to be the case if the composite doesn't have that % in there. It is possible for nano composites to have dielectric constants so high that they are unintelligible if there is a substantial charge injection effect going place. To increase the dielectric constant of the material, the first step is to fill the electroactive polymer with high charge-conducting filler particles. This is the only course of action that can be taken, and it is the only one that can be accomplished.

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