Mechanics of Advanced Composite Structures

Journal homepage: https://macs.semnan.ac.ir/

Semnan University

ISSN:2423-7043

Research Article

Dielectric and Thermal Behaviour Analysis of Epoxy Composites Filled with Date Seed Particles using Finite Element Method

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ARTICLE INFO

Article history:

Received:
Revised:
Accepted:

Keywords:

Epoxy composites;
Date seed particle;
Thermal characterization;
Conductivity;
Dielectric constant;

ABSTRACT

This study reports the thermal and dielectric behaviours of epoxy composites filled with date seed particles. DSP-epoxy composites are fabricated by adding date seed powder into epoxy resin at varying weight (0-25 %) and volume (0-17.95 %) fractions using a hand layup technique. The thermal conductivity of the composites is measured by UnithermTM2022 and HIOKI-3532-50 Hi Tester ElsierAnalyzer determines the dielectric constant. The finite element method (FEM) using Digimat FE software is used to simulate the thermal conductivity of the DSP-epoxy composites. The result showed that the thermal conductivity of the epoxy reduced by 27 % from 0.362 W/ m-K to 0.261 W/ m-K with the addition of 17.95 vol. % of DSP. The FEM-predicted values are found to be closest to the measured values, with an error range of 6-10%. The dielectric constant of the composites increased with the addition of DSP content across all frequency ranges due to interfacial and dipolar polarization. However, the dielectric constant decreased at high frequencies due to a lag in dipole orientation.

1. Introduction

Interest in natural or green composites has been growing and has emerged as a significant trend in materials science engineering[1-3]. Due to growing concerns over environmental and health issues associated with synthetic fibers, in recent years, there has been a marked shift in the field of materials engineering towards the development of green composites[4]. Synthetic fiber-reinforced composites like glass or carbon fibers offer high strength and thermal resistance but have several significant challenges, like non-biodegradability, complex and energy-intensive manufacturing processes, high cost, and difficulties in recycling or disposal. Additionally, the production and incineration of synthetic polymers does not have a good impact on the environment or health, as it releases toxic fumes and contributes to greenhouse gas emissions, leading to long-term environmental hazards and potential occupational health risks. In the case of

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Cite this article as:
Samanta, L. D., Pradhan, P., Purohit, A., Sahoo, B. B.,andJena, H., 2025. Dielectric and Thermal Behaviour Analysis of Epoxy Composites Filled with Date Seed Particles using Finite Element Method.*Mechanics of Advanced Composite Structures*, xx(x), pp. xx-xx

green composites, commonly natural fiber-reinforced composites offer a sustainable and eco-friendly alternative[5]. This material generated from renewable resources presents a sustainable alternative to the regular synthetic composites[6]. The plant-based fibers are primarily composed of cellulose, hemi-cellulose, and lignin, which contribute to the matchless properties of these composites and make them suitable for different industrial applications[7]. Plant fibers and fillers derived from different sources, such as date palm, jute, hemp, teak wood, and walnut shell, allow in preparing tailored composite materials with unique properties to achieve the industrial requirement[8–11]. This achievement leads to an increase in research efforts in the green filler polymer composites field. The conversion of interest towards these environmentally friendly materials is driven by both ecological and economic concerns. The profusion and accessibility of natural plant-based fibers are cost-effective, which makes them suitable for manufacturer[12]. Also, less energy is required to process these materials leads to a reduction in production and a small carbon foot print[13]. One of the primary advantages of natural composites is their biodegradability, which helps in waste management. These composite materials may decompose at the end of their use due to their adverse effect on the environment is minimal[14,15]. Furthermore, due to the use of green material, the health issues related to the health with synthetic material are minimizes[16]. Date palm trees outperformed other trees such as jute, coir, sisal, and hemp due to the generation of seven tons of date palm fiber annually. Although large parts of date production are consumed as food, a substantial amount remains unused, leading to the generation of significant agricultural waste. Hence, attention is focused on investigating innovative methods for utilizing these wastages in different industrial applications. One promising approach involves utilizing date palm seed powder to prepare composites as filler material. Due to excellent mechanical, dielectric properties, and thermal stability, epoxy resin is observed as an ideal polymer matrix for making composites with date seed powder[17,18]. Assessing the transformation of heat through different building materials is important for designing energy-efficient structures[19]. Thermal conductivity and dielectric properties are the two important properties that influence the energy performance of building materials[20,21]. The thermal study helps to judge the performance of these materials in a severe environment. The dielectric property of different fiber reinforced polymer composites filled with fillers has been extensively studied over the past decades[22–24]. Though several researchers studied different properties of epoxy-based composites filled with date palm fiber[25-29], very few studies have been done on date palm seed powder-filled polymer composites[30,31]. Furthermore, there is no noticeable substantial research on the dielectric property of polymer matrix composite with date seed powder (DSP) particle in the polymer matrix composite. Research found that incorporating date palm fiber into the composites enhances the storage modulus and thermal stability of epoxy resin. According to Nwogu et al.[32], the ideal amount of date seed granules in a glass fiber composite was 40 wt. %, at which point the highest tensile, flexural, impact, and hardness values were noted. In a similar vein, Abdelhussein et al.[33] investigated date seed powder (DSP) in carbon epoxy composite and discovered that 10 wt. % of date seed particles had the best wear resistance property, and 15 wt. % DSP showed the best mechanical property. B. Jdayil et al.[34] prepared green composites for insulation using date palm waste with varying weight proportions from 10-50 wt. %. The researchers used two forms of date palm material, such as date palm wood and date seeds. As the filler content increased, both thermal conductivity and thermal diffusivity of the epoxy resin decreased. The lowest thermal conductivity value observed was 0.0712 w/m-K for composites consisting of 50 wt. % date palm seed content.Date pit flour was added to 10–40 wt. % high-density polyethylene (HDPE) by Ghazanfari et al.[35]. From 10 to 30 wt. %, mechanical strength increases with the addition of filler; however, when further filler is added, mechanical strength decreases, while specific heats and thermal conductivities rise as the proportion of date pit flour increases. In another study of date palm seed particulate in polyester, it was found that composites with 15 wt. % obtained as the optimum filler content for achieving the best mechanical property[36]. It is thought that adding date palm seed particles to matrix composites could improve their mechanical characteristics by improving the filler-matrix interaction and, consequently, their composites' qualities[31,37,38].

Date palm seed-filled epoxy composites demonstrate significant applications, particularly in cost-effective insulation materials[39]. These applications include composite roofing, ceilings, wall flooring, beams, and columns. Also, this technology extends to manufacturing high-quality furniture and household products. As there is limited information available on the effects of date palm seed dust particles on the dielectric and thermal properties of epoxy composites, this study highlights the influence of date palm seed dust on thermal and dielectric behaviour of epoxy composites, and provides insight into the development of more sustainable and efficient materials.

2. Materials and Methods

2.1. Matrix Material and Filler Material

Epoxy resin with a density of 1.3 g/cm^3 serves as the primary polymer material in this study. The matrix material used in this study is a composite of unsaturated epoxy resin (1.3 g/cm^3) and its corresponding hardener, purchased from Testing Instrument Manufacturer, Kolkata. Epoxy resin is one of the widely used polymers due to some characteristics such as excellent adhesion, chemical resistance, and high tensile strength. The reinforcement was derived from date seeds, obtained from local sources. After extracting the seeds from the fruit, they are dried in sunlight for 48 hours to remove moisture. To make the powder, the dried seeds are put in a tumbler ball mill machine for eight hours. When the powder is ready, a sieve shaker should be used to separate it into particles as small as 100 microns.

2.2. Composite Fabrication

The date seed powder (DSP) reinforced epoxy composites are prepared using a meticulous process, which begins with mixing the epoxy resin and its hardener in a ratio of 10:1 as suggested by the supplier. Date seed particles (DSP) are then reinforced into the mixture using mechanical stirring to ensure even wetting and dispersion. Composite specimens were fabricated with varying weight and volume percentages by using a simple hand layup technique. To facilitate the easy removal of the composites, the mould surface is coated with mould mold-releasing sheet. The castings are taken out of the mould after curing for 24 hours. The dielectric and thermal properties of DSP-epoxy composites are investigated for DSP content ranging from 0-25 wt. % and 0-17.95 vol. % respectively. The details of fabricated composite specimens are listed in Table 1.

Table 1. Different composition of fabricated composites

Designation of composites	The weight fraction of filler and epoxy (%)		The volume fraction of filler and epoxy (%)	
	SET-1		SET-2	
	Epoxy	Date seed particle	Epoxy	Date seed particle
$EDSP_1$	100	0	100	0
$EDSP_2$	95	5	98.86	1.14
$EDSP_3$	90	10	96.65	3.35
$EDSP_4$	85	15	93.48	6.52
$EDSP_5$	80	20	88.7	11.30
$EDSP_6$	75	25	82.05	17.95

3. Thermal and Dielectric Characterization

3.1. Thermal Conductivity Measurement

Thermal conductivity is an important property in materials science and engineering that quantifies the ability of a material to conduct heat. It is expressed as the rate at which heat energy is transferred through a material per unit thickness per unit area and per unit temperature difference. In the context of this study, the thermal conductivity of the composite samples is being measured using Unitherm™2022. The experiments are carried out with circular specimens of specific dimensions; 40 mm in diameter and 5 mm in thickness. These standardised dimensions ensure consistency in thermal conductivity measurement and permit precise comparison between different composite samples. The choice of a circular geometry may be influenced by different factors such as testing instrument capability, nature of composite samples, and testing procedures.

3.2. Dielectric Characterization

The concept of dielectric was first coined by William Whewell, who referred to highly polarised material that possesses unique electrical properties. Unlike conductors, which permit the free movement of electric charges, dielectric materials constrict charge movement when placed in an electric field. This restriction causes dielectric polarization, where positive

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charges move towards the field and negative charges shift in the opposite direction. This internal charge redistribution creates an internal electric field that opposes and reduces the overall field within the dielectric material. Dielectric characterization is very important in analyzing the ability of a material to store and release electrical energy. The dielectric constant also quantifies the polarization ability of a material in an electric field. In this study, the HIOKI-3532-50 Hi Tester ElsierAnalyzer is used to measure the dielectric constant of the composite samples. The disc-type composite samples with coated silver paste act as conductive plates. The dielectric plates are then measured between 1000 Hz and 1 MHz, providing valuable insights into the electrical behaviour of the material.

3.3. Finite Element Method

The finite element method introduced by Turner et al. became a milestone in computational engineering, which offers an approximate solution to complex engineering, when boundary conditions are specified. The strength of this method lies in its ability to divide the domain into separate subdomains and apply a systematic approximate function to each using the weighted residual method. This approach permits a more manageable and precise analysis for complex problems. This research utilizes Digimat FE software to predict thermal conductivity of DSP-epoxy composite samples with 0-17.95 vol. %. This software is used to determine K_{eff} of the DSP-epoxy composites under more realistic conditions, providing a comprehensive understanding of the thermal behaviour of the material. The detailed simulation of composite materials can be performed by Digimat FE software, in which the complex behaviour of the material is considered.

4. Results and Discussion

4.1. Thermal Conductivity

The experimental findings presented in Figure 1 demonstrate that the inclusion of micro-sized date seed powder in the epoxy resin significantly improves its thermal insulation properties. The thermal conductivity of epoxy resin is downgraded by approximately 27 % from 0.362W/ m-K to 0.261W/ m-K upon addition of 17.95 vol. % of date seed powder. A similar observation was reported by[40] Ghazi et al.[40] When DSP was added to the epoxy matrix ranging from 0 to 30 wt. % of filler, it led to a decrease in thermal conductivity. Minimum thermal conductivity is observed at 30 wt. % of filler, with a value is 0.138 W/ m-K. It has also been found that the addition of filler in fiber-reinforced polymer composite improves the insulation property of the composite. [41].

This substantial improvement in heat insulation may be attributed to two factors: the inherent low thermal conductivity of date seed powder (0.07 W/ m-K) and the thermal resistance offered at the interference of date seed powder and epoxy resin. Adding a low-conducting filler to polymers may reduce the overall thermal conductivity by replacing a portion of the volume of higher-conductivity polymers. Fillers also interfere with the orderly organisation of polymer chains, which prevents heat from conduction through the matrix.[40]. Furthermore, the composite material's superior insulating properties may be partially attributed to the presence of air pockets, as air is considered to have poor thermal conductivity of heat. Although increasing DSP content beyond 17.95 vol. % could potentially further reduce thermal conductivity, this is not possible due to percolation limitation in the existing manufacturing process. To address this constraint and potentially enhance insulation properties, future research may be conducted with compression moulding or injection moulding. These methods might facilitate the inclusion of an additional 5 to 10 vol. % of filler into the polymer resin. The improved thermal insulation characteristics of DSP-epoxy composites make them suitable for use in building materials where heat loss could be significantly reduced. This may lead to substantial energy conservation and, alternatively, improve energy efficiency of the building.

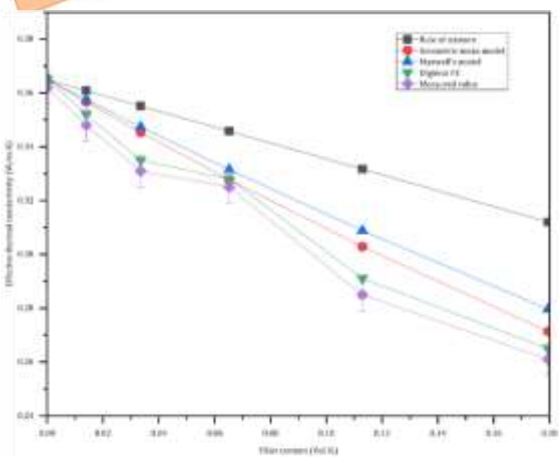
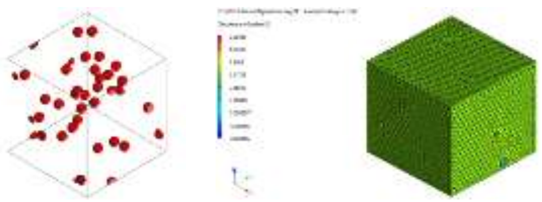


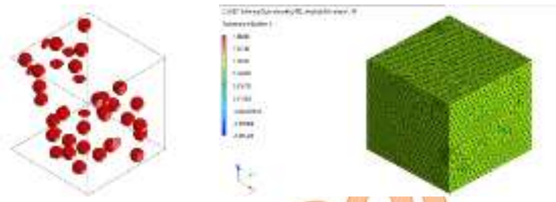
Fig. 1. Variation of thermal conductivity of DSP-epoxy composites with different filler content

4.2. Finite Element Method

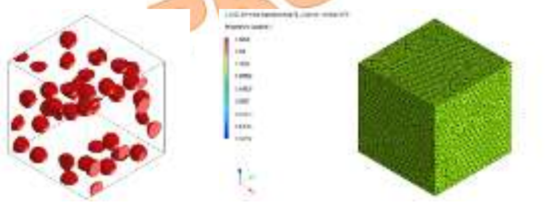
The thermal conductivity of DSP-epoxy composites with randomly distributed DSP fillers is numerically predicted using Digimat FE software. This software creates a stochastic 3D representative volume element (RVE), which represents the minimum composite consisting of all microstructural information. Digimat FE automatically generates the RVE based on the input of material data and produces mean homogenized values through a probability distribution function. The integrated mesh, solver, and post-processor of the Digimat FE software produce expedited analysis of the macro-scale behaviour of the composite. In this study, faces of the element are applied by periodic boundary conditions. The representative volume element, heat flux, and temperature gradient of the DSP-epoxy composites with different volume fractions are illustrated in Figure 2. The effective thermal conductivity of the DSP-epoxy composites is experimentally measured by the Unitherm™-2022 instrument. The measured value is compared with different theoretical models and the results predicted by Digimat software. From the comparison graph, it can be observed that the thermal conductivity of the DSP-epoxy composites degraded with the inclusion of DSP filler content. Among all the predicted values, the Digimat FE software values are found to be closest to the measured value. Error ranges for the different models obtained as: rule of mixture (1-16%), geometric mean model (1-3%), Maxwell model (1-6%), and numerical analysis (1-2%). The measured values are slightly less than all the models, which may be attributed to various factors not accounted for in the theoretical and numerical approaches. The porosity, internal thermal resistance, geometric, and boundary assumptions are the factors behind the discrepancy between the experimental and simulated results. The RVE and temperature profile of DSP-epoxy composites with different filler content are presented in Figure 2.



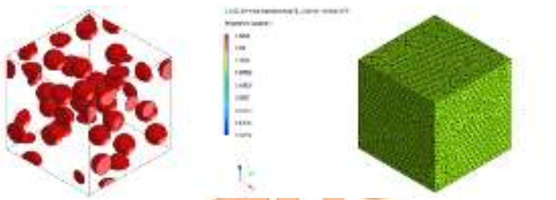
V_f=11.93%



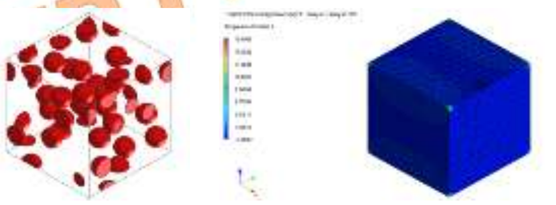
V_f=17.95%



V_f=17.95%



V_f=6.52%



V_f=6.52%

Fig. 2. RVE and temperature profile of DSP-epoxy composites

4.3. Dielectric Characterization

The polarizability is the prime reason behind the variation in the dielectric constant of the material. High molecular polarizability of the material leads to an increase in dielectric value. But the dielectric constant of the polymeric material primarily depends on the dipole, polarization, electronic, atomic, and interface factors. Figure 3 shows the variation in the constant of the DSP-epoxy composites with different filler contents. The dielectric constant of the DSP-epoxy composites increases with the addition of DSP content across all the frequency ranges. Pure epoxy shows the lowest dielectric constant of 2.5 at 1000 kHz frequency. A similar observation was found in the case of coconut husk bio-char filler in Caryota urens fiber epoxy matrix composite[22]. The addition of filler increases the dielectric constant for all frequency range and observed a maximum at 7 vol. % of filler. The increase in dielectric constant following the addition of fillers to a polymer matrix may be explained by a number of interconnected mechanisms. These are interfacial polarisation, intrinsic permittivity of filler, and filler dispersion behaviour[42].

Epoxy resin primarily consists of carbon and hydrogen atoms and possesses few permanent dipoles, leading to a lower dielectric constant. The inclusion of date seed powder creates a heterogeneous material interface and dipolar polarization. This interfacial polarization increased with a rise in the DSP content in the composites, resulting in an improvement in the dielectric constant of the DSP-epoxy composites. But it is also found that the dielectric constant tends to decrease at high frequencies. This may be attributed to a lag in orientation at dipoles. This study of dielectric behaviour is very important for developing insulation materials for the electrical and electronic industries. The inclusion of date seed powder simultaneously improves the dielectric constant and sustainability of the composite materials. This approach partially helps fulfill the growing demand for green alternatives in the electronics and electrical industries.

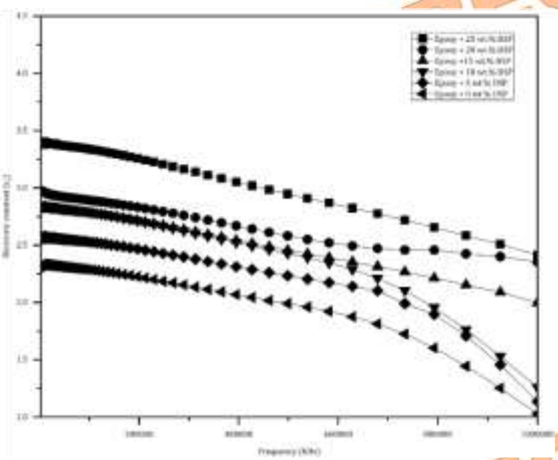


Fig. 3. Variation of Dielectric constant values of DSP-epoxy composites with different filler content

5. Conclusions

This study investigated the thermal and dielectric properties of epoxy composites filled with date seed particles (DSP). The incorporation of DSP into epoxy resin significantly improved its thermal insulation properties, with thermal conductivity decreasing by 27 % from 0.362 W/m-K to 0.261 W/m-K upon addition of 17.95 vol. % of DSP. This improvement is attributed to the low thermal conductivity of DSP and the thermal resistance at the DSP-epoxy interface. Finite element analysis using Digimat FE software provided the closest prediction to experimental thermal conductivity values, with an error range of 1-6%. This numerical approach offers valuable insights into the thermal behaviour of DSP-epoxy composites under realistic conditions. The dielectric constant of the composites increased with DSP content across all frequency ranges due to interfacial and dipolar polarization. However, a decrease in dielectric constant was observed at higher frequencies, likely due to a lag in dipole orientation. These findings highlight the potential of DSP-epoxy composites for applications in building materials, particularly for improving energy efficiency through enhanced thermal insulation. Additionally, the improved dielectric properties make these composites suitable for use in electrical and electronic industries, offering a more sustainable alternative to conventional materials.

Conflicts of Interest

There is no conflict of interest regarding the publication of this article.

Funding Statement

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Authors' contributions

Lokanath Dhalasamanta: conceptualization, methodology, investigation, writing-original draft preparation, visualization. Priyabrat Pradhan: conceptualization, validation, resources. Abhilash Purohit: writing, reviewing, and editing, supervision, project administration, and funding acquisition. Bibhuti Bhusan Sahoo: writing-original draft preparation, and visualization. Hemalata Jena: methodology, resources.

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