FABRICATION AND CHARACTERISATION OF POLYTETRAFLUOROETHYLENE-BOROSILICATE AND POLYTETRAFLUOROETHYLENE-SODA LIME SILICA GLASS COMPOSITES FOR MICROWAVE SUBSTRATE APPLICATION

By

ALHAJI IBRAHIM ABUBAKAR

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfillment of the Requirement for the Degree of Philosophy

June 2022

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DEDICATION

To my brothers in this journey, do not despair. Know that the promise of the Gatherer is certain. Be patient. Khairan zahiran, amin summa amin.

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the Degree of Doctor of Philosophy

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June 2022

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Rapid and unprecedented developments in the information technology and telecommunication industry demands high-speed, light and low-cost microwave substrates for high-frequency applications. This work presents the preparation of low-cost composites using borosilicate (BRS) and soda lime silicate (SLS) glasses. The glasses were used as fillers in the polytetrafluoroethylene (PTFE) matrix as a replacement for woven fiberglass and ceramics to reduce the cost and improve the performance of PTFE-based composites for microwave substrate application. The BRS and SLS glass powders were recycled using glass waste through ball milling. The dependence of the complex permittivity on BRS and SLS grain sizes was determined. A 63 µm grain size fillers were selected to fill the PTFE matrix through a dry powder processing technique. Surface morphology and material composition were analysed using X-ray diffraction (XRD), scanning electron microscopy (SEM), and energy-dispersive X-ray (EDX). Tensile strength, coefficient of thermal expansion (CTE), density, and moisture absorption of the composites were studied with respect to filler size and content.

The dielectric properties were characterised from 8 GHz to 12 GHz for a rectangular waveguide (RWG) and from 1 GHz to 12 GHz for an open-ended coaxial probe (OCP). In addition, the characterisation was conducted at room temperature using a vector network analyser. Similarly, the RWG was used to measure the magnitude of reflection (|S11|) and transmission (|S21|) coefficients. The results of the OCP and RWG methods indicated that the dielectric properties of all composites increased with filler content, however, the RWG method exhibited higher values than the OCP method due to the presence of air gaps in the latter method. At 10 GHz frequency, the dielectric constant (ε'), loss factor (ε'') and loss tangent (tanδ) of PTFE/BRS and PTFE/SLS composites

varied from 2.11, 0.0022, 0.0011 and 2.11, 0.0022, 0.0011 to 2.24, 0.0029, 0.0013 and 2.57, 0.0031, 0.0012, respectively, for the OCP method. For the RWG method, the ε', ε'', and tanδ had a respective change from 2.16, 0.0035, 0.0015, and 2.18, 0.0035, 0.0016 to 2.31, 0.0042, 0.0018 and 2.57, 0.0047, 0.0018 when filler content was varied from 5 wt.% to 25 wt.%. In addition, the results of $|S_{11}|$ and $|S_{21}|$ were used to calculate the power loss (dB) for the different volume fractions of PTFE/BRS and PTFE/SLS composites. The power loss at 10 GHz frequency was found to be from 3.33 dB and 3.48 dB to 3.89 dB and 3.85 dB in that order. Furthermore, the electric field distribution through the dielectric composites in the RWG was visualised for various filler content and then used to calculate the attenuation of the electric field intensity. The attenuation was found to increase from 3.67 dB and 3.70 dB to 3.81 dB and 3.77 dB for the PTFE/BRS and PTFE/SLS composites, respectively, when the filler content was adjusted from 5 wt.% to 25 wt.%.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

FABRIKASI DAN PENCIRIAN KOMPOSIT KACA POLITETRAFLUOROETILENA-BOROSILIKAT DAN POLITETRAFLUOROETILENA- SODA KAPUR SILIKA BAGI APLIKASI SUBTRAT GELOMBANG MIKRO

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Perkembangan pesat dalam teknologi maklumat dan industri telekomunikasi memerlukan substrat gelombang mikro berkelajuan tinggi, ringan dan murah untuk aplikasi frekuensi tinggi. Dalam kajian ini, penyediaan komposit kos rendah menggunakan kaca borosilikat (BRS) dan soda kapur silika (SLS). Kaca digunakan sebagai pengisi dalam matriks politetrafluoroetilena (PTFE) sebagai gantian kepada kaca gentian teranyam dan seramik untuk mengurangkan kos dan meningkatkan prestasi komposit berasaskan PTFE bagi aplikasi substrat gelombang mikro.. Serbuk kaca BRS dan SLS dikitar semula menggunakan sisa kaca melalui pengisaran bebola. Kebergantungan ketelusan kompleks pada saiz butiran BRS dan SLS telah ditentukan. Pengisi bersaiz butiran 63 μm dipilih untuk mengisi matriks PTFE melalui teknik pemprosesan serbuk kering. Morfologi permukaan dan komposisi bahan dianalisis menggunakan belauan sinar-X (XRD), mikroskopi elektron pengimbasan (SEM), dan penyebaran tenaga sinar-X (EDX). Kekuatan tegangan, pekali pengembangan haba (CTE), ketumpatan, dan penyerapan kelembapan bagi komposit telah dikaji dengan ukuran dan kandungan pengisi.

Sifat dielektrik dicirikan dari 8 GHz hingga 12 GHz untuk pandu gelombang segi empat tepat (RWG) dan dari 1 GHz hingga 12 GHz untuk kuar sepaksi terbuka (OCP). Di samping itu, pencirian dilakukan menggunakan penganalisis rangkaian vektor pada suhu bilik. RWG juga digunakan untuk mengukur pekali magnitud pantulan ($|S_{11}|$) dan pekali pemancaran ($|S_{21}|$). Hasil kaedah OCP dan RWG menunjukkan bahawa sifat dielektrik bagi semua komposit meningkat dengan kandungan pengisi, bagaimanapun, kaedah RWG menunjukkan nilai yang lebih tinggi daripada kaedah OCP kerana adanya ruang udara dalam kaedah OCP. Bagi kaedah OCP, pada frekuensi 10 GHz, ketelusan relatif (ε'), faktor kehilangan (ε'') dan tangen hilangan (tanδ) bagi komposit PTFE/BRS dan

PTFE/SLS bebeza-beza dari 2.11, 0.0022, 0.0011 dan 2.11, 0.0022, 0.0011 hingga 2.24, 0.0029, 0.0013 dan 2.57, 0.0031, 0.0012, masing-masing. Untuk kaedah RWG, ε', ε'', dan tanδ mempunyai perubahan masing-masing dari 2.16, 0.0035, 0.0015, dan 2.18, 0.0035, 0.0016 hingga 2.31, 0.0042, 0.0018 dan 2.57, 0.0047, 0.0018 apabila kandungan pengisi bervariasi dari 5 wt. % hingga 25 wt.%. Di samping itu, keputusan $|S_{11}|$ dan $|S_{21}|$ telah digunakan untuk mengira kehilangan kuasa (dB) untuk pecahan isipadu yang berbeza untuk komposit PTFE/BRS dan PTFE/SLS. Kehilangan kuasa pada frekuensi 10 GHz didapati dari 3.33 dB dan 3.48 dB hingga 3.89 dB dan 3.85 dB dalam urutan tersebut. Selanjutnya, sebaran medan elektrik melalui komposit dielektrik dalam RWG digambarkan untuk pelbagai kandungan pengisi dan kemudian digunakan untuk mengira pelemahan keamatan medan elektrik. Pelemahan didapati meningkat dari 3.67 dB dan 3.70 dB menjadi 3.81 dB dan 3.77 dB untuk komposit PTFE/BRS dan PTFE/SLS, masing-masing, apabila kandungan pengisi dilaraskan dari 5 wt. % hingga 25 wt.%.

ACKNOWLEDGEMENTS

All praise and glory be to the creator of the skies; the First, the Last, the Manifest, and the Hidden One. May the peace and blessing of the Light be upon our Master (Sallallahu Alaihi Wasallam) through whom all knowledge is received.

I would like to extend my heartfelt gratitude to the Chairman of my supervisory committee, Associate Prof. Dr. Zulkifly Abbas for his fatherly guidance, encouragement, thoughtful criticisms, and support throughout this research period. I would also like to thank other supervisory committee members, Dr Mohd Hafiz Mohd Zaid and Dr Norhazlin Zainuddin, for their support, encouragement, and guidance. May you all be rewarded abundantly, amin. Mentioned must be made of my former co-supervisor, Associate Prof. Dr Nor Azowa Ibrahim, who retired from UPM. I thank you for your patience and helpful criticism toward refining this work. I wish you a happy retirement and all the best life can offer.

My deepest gratitude goes to my family (from the oldest to the youngest) for always being there for me. Words cannot quantify my appreciation to you for being with me during this challenging time. You will always come first.

I also wish to acknowledge past and present RF and Microwave laboratory members, especially Dr Ebenezer Ekow Mensah and Ahmad Mamoun Khamis. I appreciate Dr Mensah for his helpful and wise counsel. I say to Ahmad Mamoun Khamis that words cannot describe the support you rendered to me during our journey. You are just a wonderful person. I appreciate being your colleague and wish you all the best.

Finally, I wish to thank the Federal University of Kashere for allowing me to pursue doctoral studies through the TETFUND fellowship.

This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

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LIST OF ABBREVIATIONS

PTFE	Polytetrafluoroethylene (Teflon)
BRS	Borosilicate
SLS	Soda lime Silica
OCP	Open-ended coaxial probe
RWG	Rectangular waveguide
EF	Electric field
XRD	X-ray diffraction
SEM	Scanning Electron Microscope
EDX	Energy dispersive x-ray
ICSD	Inorganic crystal structure database
CTE	Coefficient of thermal expansion
FEM	Finite element method
FDTD	Finite difference time domain
VNA	Vector network analyser
TRL	Thru, Reflect, Line
RF	Radio frequency
ECAL	Electronic calibration
TR	Transmission/Reflection
S_{11}	Reflection coefficient
S_{21}	Transmission coefficient
ε^*	Complex permittivity
ε'	Dielectric constant/relative permittivity
ε''	Loss factor

CHAPTER 1

INTRODUCTION

The last decade has witnessed a rapid and unprecedented development in information technology and telecommunication industries driven by military and consumer markets (Manu et al., 2013; Hao Wang et al., 2020; C. Xie et al., 2017). This sudden change creates a high demand for high-speed, light and low-cost microwave substrates. A microwave base substrate that meets specific criteria, supports the microwave circuits (Ren et al., 2018; Tan et al., 2022; Varghese et al., 2015). Microwave substrates are dielectric materials with moderate permittivity and low loss tangent at microwave frequencies (Li et al., 2021). The substrate candidate materials should possess a low dielectric constant to reduce signal propagation delay, a small magnitude of thermal expansion coefficient (CTE) to avoid a mismatch between the conductor and the substrate material, a high thermal conductivity (TC) to transport the heat generated away from the circuits at high frequencies (> 1 GHz) and good mechanical strength (Murali et al., 2009; Tan et al., 2021). Polymers are widely used for substrate applications due to their low dielectric constant and chemical inertness, but they have a high thermal expansion coefficient and low thermal conductivity (Han et al., 2020; Thomas et al., 2016). However, polytetrafluoroethylene (PTFE) is the most widely used among polymers due to its low dielectric loss and low moisture absorption, but it has a high melting point, making it difficult to process. PTFE is crystalline and has a broad range of applications as an excellent insulator from high electrical power to defence industries (Venkateswarlu et al., 2015; Zhou et al., 2020). Generally, the properties of polymers depend on their microstructure and composition as such suitable fillers of varying sizes and content should be used to fill and strengthen the polymers (Thomas et al., 2016). Several studies have been conducted to improve PTFE's thermal, mechanical and dielectric properties (Han et al., 2020; Shamsuddin et al., 2020; Varghese et al., 2015; C. Xie et al., 2017; Jie Yang et al., 2020). To enhance the thermal and mechanical properties of PTFE without affecting its electrical properties, a filler with a low dielectric constant and CTE and high tensile strength is required. Most practical demands to control the properties of the PTFE can be addressed by incorporating glass fillers such as borosilicate (BRS) and soda lime silica (SLS) glasses as they have high thermal conductivity and tensile strength, low CTE, and moderate dielectric constant (Ashby, 2012; Bruns et al., 2020a; Karasu et al., 2020; Khazaalah et al., 2022).

1.1 Problem Statement

Commercial fibreglass and ceramic are the most commonly used fillers to produce PTFE-based microwave substrates due to their good electrical, thermal and mechanical properties (Luo et al., 2018; H. Wang et al., 2020). However, the increased demand for high-speed and low-cost microwave substrates demands alternative lower-cost filler materials to sustain the industry's advancement and reduce the cost of microwave substrates for consumers. Therefore, this research proposes a new technique to reduce the cost of polymer-based composites by using recycled BRS and SLS glass waste in combination with a PTFE matrix. The BRS and SLS glasses have comparable dielectric and mechanical properties to the commercial fillers. However, the glasses possess better rigidity and lower CTE. Furthermore, the technique involves extracting glass powders from the BRS and SLS waste and following optimisation of the dielectric properties by reducing the particle size to micrometre sizes through ball milling. The relationship between grain size and the dielectric properties of the BRS and SLS powders was then determined. The BRS and SLS powders with optimum dielectric properties could reduce the cost of inorganic fillers for microwave substrates and further eliminate environmental pollution without compromising performance.

PTFE is a carbon-based, fluorinated synthetic polymer (Kecerdasan & Ikep, 2017). It has outstanding dielectric and moisture absorption properties that make it the most preferable among polymers for microwave substrate application (Zhang et al., 2022). However, its high CTE, lack of rigidity, and high processing temperature pose a challenge to its handling for practical application (Q. Li et al., 2021). The inclusion of BRS and SLS fillers into the PTFE matrix through a simple dry powder processing method could easily remedy the processing obstacles and produce composites with well-adjusted dielectric, mechanical, and thermal properties suitable for microwave substrate application. Also, the BRS and SLS particle sizes could affect the dielectric, mechanical, and thermal properties of the PTFE/BRS and PTFE/SLS composites, which have to be examined. Moreover, composites must have low dielectric properties for high-speed data transmission. Therefore, an optimum filler size of 63 μm for the BRS and SLS was fed into the PTFE/BRS and PTFE/SLS to enhance the mechanical and thermal properties without adversely affecting the dielectric properties of the PTFE matrix.

The conventional measurement technique used to characterise the dielectric properties of the PTFE/BRS and PTFE/SLS composites was the open-ended coaxial probe (OCP). The technique has the advantage of being simple to implement and easy to prepare a sample for measurement (Aydinalp et al., 2022). However, the technique suffers from the wrong assumption that samples are homogeneous and isotropic within the volume of the measurement probe (Brace & Etoz, 2020). Moreover, the technique is one-port, thus, it could not characterise the scattering parameters (S_{11} *and* S_{21}) of the composites. The S_{11} *and* S_{21} are fundamental to determining the power loss in the composites due to absorption. In this research, a rectangular waveguide (RWG) measurement technique was used, in addition to the OCP technique, to measure the dielectric properties as well as the S_{11} *and* S_{21} of the PTFE/BRS and PTFE/SLS composites. The dielectric results from the RWG technique were used as inputs to the COMSOL software using the finite element method (FEM) to calculate the S_{11} and S_{21} and visualised the electric field distribution in the composites.

1.2 Research Objectives

This research prepares, fabricates and characterises PTFE/BRS and PTFE/SLS on their structural, morphology and dielectric properties. The specific objectives of the study are:

I. To fabricate PTFE/BRS and PTFE/SLS composites with different filler sizes to investigate the effect of the filler size on the mechanical, thermal, and dielectric properties of the composites.

II. To fabricate PTFE/BRS and PTFE/SLS composites with different filler volume fractions to examine the effect of filler content on the structural, mechanical, thermal, and dielectric properties of the composites

III. To examine the effect of recycled BRS and SLS fillers on the S_{11}, S_{21} and power loss due to absorption for the PTFE/BRS and PTFE/ SLS composites. The experimentally measured $|S_{11}|$ *and* $|S_{21}|$ would be compared with those calculated from the FEM implemented in COMSOL software.

IV. To visualise the electric field distribution across dielectric samples and calculate the attenuation of the field intensity due to filler content.

1.3 Scope of the Study

This research prepares recycled BRS and SLS powders from glass waste. The powders will be reduced into five micro sizes using a high ball milling technique for twenty-four hours. The complex permittivity of the recycled glass powders will be measured in the microwave frequency range of 1–12 GHz. The first set of composites will be fabricated using recycled glass powders of different sizes at a 5 wt.% fixed concentration. The fabrication will be conducted via the powder dry processing technique to determine the optimum filler size. This filler size then will be used to fabricate the final composites. The percentage weight of the glass powders to fill the matrix will be varied from 5 wt.%-25 wt.% with a 5 wt.% increment. The structural, morphological, and compositional characterisation will be conducted using techniques of XRD, SEM, and EDX. Tensile strength, CTE, moisture absorption, and the composites' density will also be determined.

The influence of the recycled fillers on the complex permittivity of PTFE/BRS and PTFE/SLS composites will be studied using rectangular waveguide and open-ended coaxial probe techniques at 8.2 GHz- 12.4 GHz and 1 GHz -12 GHz, respectively. Similarly, the effect of the fillers on the scattering parameters will be determined using the rectangular waveguide technique. The study also calculates the scattering parameters using the finite element method (FEM) implemented in COMSOL software. Measured and computed S-parameters will be compared, and error analysis between them would be determined. The COMSOL software will also be utilised to visualise the interaction of electromagnetic waves with the dielectric samples. Attenuation of the electromagnetic intensity of the composites will be calculated via the finite element method (FEM) using COMSOL software.

1.5 Thesis Layout

The thesis consists of six chapters. Chapter 1 presents the general overview of substrate materials and the interaction of microwaves with materials. The chapter highlights the problem statement and research objectives, followed by the scope of the study and the thesis layout.

Chapter 2 looks at the literature review of some principles and presents a dry powder processing technique. The properties of PTFE, BRS, and SLS glasses were presented, along with a review of the composite preparation methods. The chapter also reviews dielectric measurement techniques and FEM formulation for calculating S-parameters.

Chapter 3 discusses the theory behind mechanical alloying and dry powder processing techniques, and the chapter presents the dielectric properties and the nature of polarisation taking place. It also discusses the basic electromagnetic wave equation and its derivation. Finally, the theory for FEM analysis is presented.

Chapter 4 consists of the methodology used in this study. The preparations of BRS and SLS glass powders are discussed. PTFE/BRS and PTFE/SLS composites fabrication process is given in detail. The use of OCP, RWG, and FEM concerning dielectric characterisation is thoroughly discussed. The methods for characterising tensile and CTE are also provided. The structural, morphological, and compositional techniques are also presented.

Chapter 5 gives the results of the entire characterisation carried out. Sections 5.1 and 5.2 discuss the results for XRD, SEM, and EDX. This is followed by a discussion on the results from moisture absorption, density, tensile strength and CTE in sections 5.3, 5.4, 5.5, and 5.6. The complex permittivity results from the open-ended coaxial probe and rectangular waveguide techniques are discussed in sections 5.7 and 5.8. Section 5.9 discusses the S-parameters results calculated from RWG and FEM. Section 5.10 discusses the power loss due to material absorption, while section 5.11 discusses electrical field distribution and its attenuation.

Chapter 6 summarises the study and recommends future work.

REFERENCES

Abdalhadi, D. M. (2018). *Fabrication and characteristics of oil palm fibre-reinforced polylactic acid composite filled with iron oxide for microwave application*. (Unpublished doctoral thesis). Universiti Putra Malaysia.

Abdalhadi, D. M., Abbas, Z., Ahmad, A. F., Matori, K. A., & Esa, F. (2018). Controlling the Properties of OPEFB/PLA Polymer Composite by Using Fe2O3 for Microwave Applications. *Fibers and Polymers*, *19*(7), 1513–1521.

Abdelrazek, E. M., Abdelghany, A. M., Badr, S. I., & Morsi, M. A. (2018). Structural, optical, morphological and thermal properties of PEO/PVP blend containing different concentrations of biosynthesized Au nanoparticles. *Journal of Materials Research and Technology*, *7*(4), 419–431.

Abubakar, Y. (2015). *Synthesis and Characterization of Zinc Oxide Polycaprolactone Nanocomposites using Rectangular Waveguide and Microstrip Techniques*. (Unpublished doctoral thesis). Univerisiti Putra Malaysia.

Advanced Connectivity Solution. (2021). *AD Series® Laminates*. https://rogerscorp.com/advanced-connectivity-solutions/ad-series-laminates (access 23 Jan. 2021).

Ahmad, P., Rao, A. V., Babu, K. S., & Rao, G. N. (2019). Particle size effect on the dielectric properties of ZnO nanoparticles. *Materials Chemistry and Physics*, *224*(February 2018), 79–84.

Al-Maharma, A. Y., Patil, S. P., & Markert, B. (2020). Effects of porosity on the mechanical properties of additively manufactured components: a critical review. *Materials Research Express*, *7*(12).

Al-Shroofy, M., Zhang, Q., Xu, J., Chen, T., Kaur, A. P., & Cheng, Y. T. (2017). Solvent-free dry powder coating process for low-cost manufacturing of LiNi1/3Mn1/3Co1/3O2 cathodes in lithium-ion batteries. *Journal of Power Sources*, *352*, 187–193.

Ali, A., Chiang, Y. W., & Santos, R. M. (2022). X-Ray Diffraction Techniques for Mineral Characterization: A Review for Engineers of the Fundamentals, Applications, and Research Directions. *Minerals*, *12*(2).

An, Z., Li, J., Kikuchi, A., & Wang, Z. (2019). Mechanically strengthened graphene-Cu composite with reduced thermal expansion towards interconnect applications. *Microsystems & Nanoengineering*.

Andritsch, T. (2010). *Epoxy Based Nanodielectrics for High Voltage DC-Applications–Synthesis, Dielectric Properties and Space Charge Dynamics*. (Unpublished doctoral research). Technische Universiteit Delft.

Anjana, P. S., Deepu, V., Uma, S., Mohanan, P., Philip, J., & Sebastian, M. T.

(2010). Dielectric, thermal, and mechanical properties of CeO_2-filled HDPE composites for microwave substrate applications. *Journal of Polymer Science, Part B: Polymer Physics*, *48*(9), 998–1008.

Ansys. (2022). *Ansys HFSS Best-In-Class 3D High Frequency Electromagnetic Simulation RF and Wireless Design*. https://www.ansys.com/products/electronics/ansys-hfss (accessed 13 Jun. 2022).

Arıbuğa, D., Akkaşoğlu, U., Çiçek, B., & Balcı-Çağıran, Ö. (2022). Enhanced Sinterability, Thermal Conductivity and Dielectric Constant of Glass-Ceramics with PVA and BN Additions. *Materials*, *15*(5).

Ashby, M. F. (2012). *Materials and the Environment*. Butterworth-Heinemann.

Awais, M., Sundararajan, R., Sajjad, I. A., Haroon, S. S., Amin, S., Shaukat, H., & Nasir, M. A. (2019). Investigation on optimal filler loadings for dielectric strength enhancement of epoxy/TiO_2@SiO_2 nanocomposite. *Materials Research Express*, *6*(6), 0–8.

Aydinalp, C., Joof, S., Dilman, I., Akduman, I., & Yilmaz, T. (2022). Characterization of Open-Ended Coaxial Probe Sensing Depth with Respect to Aperture Size for Dielectric Property. *Sensors*, *22*(760), 1–13.

Aziz, S. B., Marf, A. S., Dannoun, E. M. A., Brza, M. A., & Abdullah, R. M. (2020). The study of the degree of crystallinity, electrical equivalent circuit, and dielectric properties of polyvinyl alcohol (PVA)-based biopolymer electrolytes. *Polymers*, *12*(10), 1–17.

Babu, G. B., Winston, P. D., Bhaskar, A. P. V., Baskaran, R., & Narayanasamy, P. (2021). Exploration of Electrical, Thermal, and Mechanical Properties of Phaseolus vulgaris Fiber/Unsaturated Polyester Resin Composite Filled with Nano–SiO_2. *Journal of Natural Fibers*, *18*(12), 2156–2172.

Boiko, O., Drozdenko, D., & Minárik, P. (2022). Dielectric properties, polarization process, and charge transport in granular (FeCoZr)x(Pb(ZrTi)O_3)(100-x)nanocomposites near the percolation threshold. *AIP Advances*, *12*(2).

Borhan, A. I., Gromada, M., Nedelcu, G. G., & Leontie, L. (2016). Influence of (CoO, CaO, B_2O_3) additives on thermal and dielectric properties of BaO-Al_2O_3-SiO_2 glass-ceramic sealant for OTM applications. *Ceramics International*, *42*(8), 10459–10468.

Brace, C. L., & Etoz, S. (2020). An analysis of open-ended coaxial probe sensitivity to heterogeneous media. *Sensors (Switzerland)*, *20*(18), 1–13.

Britannica, T. (2019). *Polytetrafluoroethylene*. Encyclopedia Britannica. https://www.britannica.com/science/polytetrafluoroethylene (accessed 12 Jun. 2022).

Bruns, S., Uesbeck, T., Weil, D., Möncke, D., van Wüllen, L., Durst, K., & de Ligny, D. (2020a). Influence of Al_2O_3 Addition on Structure and Mechanical

Properties of Borosilicate Glasses. In *Frontiers in Materials* (Vol. 7).

Bruns, S., Uesbeck, T., Weil, D., Möncke, D., van Wüllen, L., Durst, K., & de Ligny, D. (2020b). Influence of Al2O3 Addition on Structure and Mechanical Properties of Borosilicate Glasses. *Frontiers in Materials*, *7*(July).

Cai, X., Dong, X., Lv, W., Ji, C., Jiang, Z., Zhang, X., … Zhang, X. (2020). Synergistic enhancement of thermal conductivity for low dielectric constant boron nitride–polytetrafluoroethylene composites by adding small content of graphene nanosheets. *Composites Communications*, *17*(November 2019), 163–169.

Chaichanawong, J., Thongchuea, C., & Areerat, S. (2016). Effect of moisture on the mechanical properties of glass fiber reinforced polyamide composites. *Advanced Powder Technology*, *27*(3), 898–902.

Chen, L. F., Ong, C. K., Neo, C. P., Veradan, V. V., & Veradan, V. K. (2004). *Microwave Electronics: Measurement and Materials Characterization*. John Wiley & Sons, Ltd.

Chen, Y. C., Lin, H. C., & Lee, Y. Der. (2003). The Effects of Filler Content and Size on the Properties of PTFE/SiO 2 Composites. *Journal of Polymer Research*, *10*(4), 247–258.

Chen, Y., Yu, G., & Duan, Z. (2019). Ultra-low permittivity HSM/PTFE composites for high-frequency microwave circuit application. *Journal of Nanomaterials*, *2019*, 11.

COMSOL. (2022). *COMSOL Multiphysics® Simulation Software*. https://www.comsol.com/comsol-multiphysics (accessed 13 Jun. 2022).

Dassault, S. (2022). *CST Studio Suite ™*. https://www.3ds.com/products-services/simulia/products/cst-studio-suite/ (accessed 13 Jun. 2022).

de Paula, A. L., Rezende, M. C., & Barroso, J. J. (2011). Experimental measurements and numerical simulation of permittivity and permeability of teflon in x band. *Journal of Aerospace Technology and Management*, *3*(1), 59–64.

Dhanumalayan, E., & Joshi, G. M. (2018). Performance properties and applications of polytetrafluoroethylene (PTFE)—a review. *Advanced Composites and Hybrid Materials*, *1*(2), 247–268.

Drupitha, M. P., Naskar, K., & Nando, G. B. (2017). Compatibilized TPU-PDMS blends: Pros and cons of melt mixing and solution mixing techniques. *Journal of Applied Polymer Science*, *134*(31).

DuPont. (2011). *Teflon Properties Handbook*. DuPont Fluoroproducts.

Elloumi, I., Koubaa, A., Kharrat, W., Bradai, C., & Elloumi, A. (2021). Dielectric properties of wood-polymer composites: Effects of frequency, fiber nature, proportion, and chemical composition. *Journal of Composites Science*, *5*(6).

Fabian, M., Gergely, F., Osan, J., Cendak, T., Kesari, S., & Rao, R. (2020). Structural investigation of borosilicate glasses containing lanthanide ions. *Scientific Reports*, *10*(1), 7835.

Feng, W., Yin, L., Han, Y., Wang, J., Xiao, K., & Li, J. (2021). Tribological and physical properties of PTFE-NBR self-lubricating composites under water lubrication. *Industrial Lubrication and Tribology*, *73*(1), 82–87.

Fraga, A. N., Frullloni, E., De La Osa, O., Kenny, J. M., & Vázquez, A. (2007). Relationship between water absorption and dielectric behavior of glass fiber reinforced unsaturated polyester resin. *Journal of Composite Materials*, *41*(4), 393–402.

Francis, L. F. (2016). Powder Processes. In *Materials Processing* (pp. 343–411). Academic Press.

Francis Thoo, V. W., Zainuddin, N., Matori, K. A., & Abdullah, S. A. (2013). Studies on the potential of waste soda lime silica glass in glass ionomer cement production. *Advances in Materials Science and Engineering*, *2013*.

Gama, A. M., & Rezende, M. C. (2013). Complex permeability and permittivity variation of radar absorbing materials based on mnzn ferrite in microwave frequencies. *Materials Research*, *16*(5), 997–1001.

Gandhi, N., Singh, K., Ohlan, A., Singh, D. P., & Dhawan, S. K. (2011). Thermal, dielectric and microwave absorption properties of polyaniline-CoFe2O4 nanocomposites. *Composites Science and Technology*, *71*(15), 1754–1760.

German, R. M. (1984). Powder Methods. In *Materials Science And Engineering: Vol. II*. Metal Powder Industries Federation.

Goodfellow Ceramic & Glass Division. (2022). *Borosilicate Glass - Properties of Borosilicate Glass (Pyrex/Duran)*. https://www.azom.com/article.aspx?ArticleID=4765 (accessed 12 Jun. 2022).

Hammi, M. (2021). Surface and Interface Investigations of Matrix-Fillers in Heterogeneous Amorphous Semiconductors. *ACS Omega*, *6*(49), 34075–34085.

Han, K., Zhou, J., Li, Q., Shen, J., Qi, Y., Yao, X., & Chen, W. (2020). Effect of filler structure on the dielectric and thermal properties of SiO2/PTFE composites. *Journal of Materials Science: Materials in Electronics*, *31*(12), 9196–9202.

Hasanuzzaman, M., Rafferty, A., Sajjia, M., & Olabi, A.-G. (2016). Properties of Glass Materials. In *Reference Module in Materials Science and Materials Engineering* (pp. 1–12). Elsevier Ltd.

Hisham, N. A. N., Zaid, M. H. M., Aziz, S. H. A., & Muhammad, F. D. (2021). Comparison of foam glass-ceramics with different composition derived from ark clamshell (ACS) and soda lime silica (SLS) glass bottles sintered at various temperatures. *Materials*, *14*(3), 1–14.

Hu, T., Juuti, J., Jantunen, H., & Vilkman, T. (2007). Dielectric properties of BST/polymer composite. *Journal of the European Ceramic Society*, *27*(13–15), 3997–4001.

Huang, A., Kharbas, H., Ellingham, T., Mi, H., Turng, L. S., & Peng, X. (2017). Mechanical properties, crystallization characteristics, and foaming behavior of polytetrafluoroethylene-reinforced poly(lactic acid) composites. *Polymer Engineering and Science*, *57*(5), 570–580.

Huang, F., Yuan, Y., Jiang, Z., Tang, B., & Zhang, S. (2019). Microstructures and properties of glass fiber reinforced PTFE composite substrates with laminated construction. *Materials Research Express*, *6*(7), 0–10.

Humairah, S., Rozlin, N., Masdek, N., Mahmud, J., Mohammed, M. N., Sapuan, S. M., … Abdelrahman, A. (2022). *Morphological, Physical, and Mechanical Properties of Sugar-Palm (Arenga pinnata (Wurmb) Merr .)-Reinforced Silicone Rubber Biocomposites*.

Ighalo, J. O., Adeniyi, A. G., Owolabi, O. O., & Abdulkareem, S. A. (2021). Moisture absorption, thermal and microstructural properties of polymer composites developed from rice husk and polystyrene wastes. *International Journal of Sustainable Engineering*, *14*(5), 1049–1058.

Irshidat, M. R., Al-saleh, M. H., & Sanad, S. (2015). Effect of Nanoclay on Expansive Potential of Cement Mortar due to Alkali-Silica Reaction. *ACI Materials Journal*, *112*(1–6), 1–8.

Ismail, N. Q. A., Saat, N. K., & Zaid, M. H. M. (2020). Effect of soda lime silica glass doping on ZnO varistor ceramics: dry milling method. *Journal of Asian Ceramic Societies*, *8*(3), 909–914.

Jaafar, C. N. A., Zainol, I., Khairani, M. I. I., & Dele-Afolabi, T. T. (2022). Physical and Mechanical Properties of Tilapia Scale Hydroxyapatite-Filled High-Density Polyethylene Composites. *Polymers*, *14*(2), 1–17.

Jelić, A., Sekulić, M., Travica, M., Gržetić, J., Ugrinović, V., Marinković, A. D., … Putić, S. (2022). Determination of Mechanical Properties of Epoxy Composite Materials Reinforced with Silicate Nanofillers Using Digital Image Correlation (DIC). *Polymers*, *14*(6).

Jiang, Z. H., & Yuan, Y. (2019). Microwave dielectric properties of SrAl2Si2O8 filled Polytetrafluoroethylene composites. *IOP Conference Series: Materials Science and Engineering*, *479*(1), 1–8.

Jiang, Z., & Yuan, Y. (2018). Effects of particle size distribution of silica on properties of PTFE/SiO2 composites. *Materials Research Express*, *5*(6).

Jin, J.-M. (2014). *The Finite Element Method in Electromagnetics* (3rd ed.). John Wiley & Sons, Inc.

Joseph, T., Uma, S., Philip, J., & Sebastian, M. T. (2011). Electrical and thermal properties of PTFE-Sr 2ZnSi 2O 7 composites. *Journal of Materials Science: Materials in Electronics*, *22*(8), 1000–1009.

Joshi, S. V., & Waldorf, M. (2003). *Process for Making Polytetrafluoroethylene-Aluminum Composite and Product Made* (Patent No. US 6547993B1). United States Patent. https://patents.google.com/patent/US6547993B1/en

Karasu, B., Demirel, İ., Aydin, S., Dalkiran, M., & Lik, B. (2020). Past and present approaches to borosilicate glasses. *El-Cezeri Journal of Science and Engineering*, *7*(2), 940–969.

Karlsson, S. (2022). Compositional Effects on Indentation Mechanical Properties of Chemically Strengthened TiO2-Doped Soda Lime Silicate Glasses. *Materials*, *15*(2).

Kecerdasan, I., & Ikep, P. (2017). *Expanded PTFE Applications Handbook* (S. Ebnesajjad (ed.)). Plastics Design Library (PDL).

Keysight, T. (2002). *Keysight Technologies 11644A X, P, and K Waveguide Calibration Kits*. Keysight Technologies.

Khamis, A. M. (2019). *Development of Epoxy-OPEFB Composites for Shielding Applications*. (Unpublished master's thesis). University Putra malaysia.

Khamis, Ahmad Mamoun, Abbas, Z., Ahmad, A. F., Azis, R. S., Abdalhadi, D. M., & Mensah, E. E. (2020). Experimental and computational study on epoxy resin reinforced with micro-sized OPEFB using rectangular waveguide and finite element method. *IET Microwaves, Antennas and Propagation*, *14*(8), 752–758.

Khan, M. S., Osada, M., Kim, H. J., Ebina, Y., Sugimoto, W., & Sasaki, T. (2017). High-temperature dielectric responses in all-nanosheet capacitors. *Japanese Journal of Applied Physics*, *56*(6), 0–4.

Khazaalah, T. H., Mustafa, I. S., Sayyed, M. I., Rahman, A. A., Zaid, M. H. M., Hisam, R., … Khalib, N. C. (2022). Development of Novel Transparent Radiation Shielding Glasses by BaO Doping in Waste Soda Lime Silica (SLS) Glass. *Sustainability (Switzerland)*, *14*(2), 1–11.

Khouaja, A., Koubaa, A., & Ben, H. (2021). Industrial Crops & Products Dielectric properties and thermal stability of cellulose high-density polyethylene bio-based composites. *Industrial Crops & Products*, *171*(April), 113928.

Kittel, C. (2004). *Introduction to Solid State Physics* (8th Edit.). Wiley.

Kochetov, R. (2012). *Thermal and Electrical Properties of Nanocomposites, Including Material Properties*. (Unpublished doctoral thesis). Technische Universiteit Delft.

Kong, N., Khalil, N. Z., & Fricke, H. (2021). Moisture absorption behavior and adhesion properties of gnp/epoxy nanocomposite adhesives. *Polymers*, *13*(11), 1–17.

Kumar, A., Kumar, A., & Sharmaa, K. K. (2022). Investigation of Dielectric Properties of Ni/n-TiO2/p-Si/Al Heterojunction in Wide Range of Temperature and Voltage. *International Journal of Engineering, Transactions A: Basics*, *35*(4), 698–705.

Kundu, A., & Gupta, B. (2014). Broadband dielectric properties measurement of some vegetables and fruits using open ended coaxial probe technique. *International Conference on Control, Instrumentation, Energy and Communication, CIEC 2014*, *November*, 480–484.

La Gioia, A., Porter, E., Merunka, I., Shahzad, A., Salahuddin, S., Jones, M., & O'Halloran, M. (2018). Open-Ended Coaxial Probe Technique for Dielectric Measurement of Biological Tissues: Challenges and Common Practices. *Diagnostics*, *8*(2), 40.

LaFreniere, J. M. J., Roberge, E. J., & Halpern, J. M. (2020). Review—Reorientation of Polymers in an Applied Electric Field for Electrochemical Sensors. *Journal of The Electrochemical Society*, *167*(3), 037556.

Lago, E. D., Cagnin, E., Carlo, B., Martina, R., Lorenzetti, A., & Modesti, M. (2020). Influence of different carbon-based fillers on electrical and mechanical properties of a PC/ABS blend. *Polymers*, *12*(1).

Lakin, I. I., Abbas, Z., Azis, R. S., & Alhaji, I. A. (2020). Complex Permittivity and Electromagnetic Interference Shielding Effectiveness of OPEFB Fiber-Polylactic Acid Filled with Reduced Graphene Oxide. *Materials*, *13*(4602), 12.

Lee, C. (2020). *Novel methods of measuring dielectric properties of different shapes and sizes of materials*. (Unpublished doctoral thesis). Loughborough University.

Li, Q., Liu, P., Mahmood, K., Zhang, N., & Che, Y. (2021). Improved properties of PTFE composites filled with glass fiber modified by sol–gel method. *Journal of Materials Science: Materials in Electronics*, *32*(18), 23090–23102.

Li, Z., Liu, J., Yuan, Y., Li, E., & Wang, F. (2017). Effects of surface fluoride-functionalizing of glass fiber on the properties of PTFE/glass fiber microwave composites. *RSC Advances*, *7*(37), 22810–22817.

Luo, F., Tang, B., Fang, Z., Yuan, Y., Li, H., & Zhang, S. (2019). Effects of coupling agent on dielectric properties of PTFE based and Li2Mg3TiO6 filled composites. *Ceramics International*, *45*(16), 20458–20464.

Maloney, J. G., Smith, G. S., & SCott, W. R. (1990). Accurate Computation of the Radiation from Simple Antennas using the Finite-Difference Time-Domain Method. *IEEE Transactions on Antennas and Propagation*, *38*(7), 1059–1068.

Malte, G., Christof, K., & Rainer, E. (2019). *Borosilicate Glass Article with Low Boron Content* (Patent No. EP 3584228A2). European Patent Office.

Manu, K. M., Soni, S., Murthy, V. R. K., & Sebastian, M. T. (2013). Ba(Zn1/3Ta2/3)O3 ceramics reinforced high density polyethylene for microwave applications. *Journal of Materials Science: Materials in Electronics*, *24*(6), 2098–2105.

Marín-Genescà, M., García-Amorós, J., Mujal-Rosas, R., Vidal, L. M., & Fajula, X. C. (2020). Application properties analysis as a dielectric capacitor of end-of-life tire-reinforced hdpe. *Polymers*, *12*(11), 1–20.

Mazur, K., Gadek-Moszczak, A., Liber-Knec, A., & Kuciel, S. (2021). Mechanical Behavior and Morphological Study of. *Materials*, *14*(1712), 1–6.

Meli, A. D. (2019). *Characterisation of Lossy Low Dielectric Constant Soda Lime Silica-High Density Polyethylene Composites for Microwave Application*. (Unpublished master's thesis). Universiti Putra malaysia.

Meli, A. D., Abbas, Z., Mohd Zaid, M. H., & Ibrahim, N. A. (2019). The effects of SLS on structural and complex permittivity of SLS-HDPE composites. *Advances in Polymer Technology*, *2019*.

Mensah, E. E. (2019). *Synthesis and Electromagnetic Characterization of Polycaprolactone Filled with Hematite and OPEFB Fiber Nanocomposite*. (Unpublished doctoral thesis). Universiti Putra Malaysia.

Mensah, E. E., Abbas, Z., Azis, R. S., Ibrahim, N. A., Khamis, A. M., & Abdalhadi, D. M. (2020). Complex permittivity and power loss characteristics of α-Fe2O3/polycaprolactone (PCL) nanocomposites: effect of recycled α-Fe2O3 nanofiller. *Heliyon*, *6*(12), e05595.

Microwave & RF Laminates Products. (2020). *TLX High Volume Fiberglass Reinforced Microwave Substrate*. https://www.agc-multimaterial.com/page/microwave--rf-laminates-66.html (accessed 05 July 2021).

Murali, K. P., Rajesh, S., Nijesh, K. J., & Ratheesh, R. (2010). Effect of particle size on the microwave dielectric properties of alumina-filled PTFE substrates. *International Journal of Applied Ceramic Technology*, *7*(4), 475–481.

Murali, K. P., Rajesh, S., Prakash, O., Kulkarni, A. R., & Ratheesh, R. (2009). Preparation and properties of silica filled PTFE flexible laminates for microwave circuit applications. *Composites Part A: Applied Science and Manufacturing*, *40*(8), 1179–1185.

Nayak, R. K., Mahato, K. K., & Ray, B. C. (2016). Water absorption behavior, mechanical and thermal properties of nano TiO2 enhanced glass fiber reinforced polymer composites. *Composites Part A: Applied Science and*

Manufacturing, *90*, 736–747.

Oladele, I. O., Omotosho, T. F., & Adediran, A. A. (2020). Polymer-Based Composites: An Indispensable Material for Present and Future Applications. *International Journal of Polymer Science*, *2020*.

Omah, A. D., Ugwuogbo, E. E., & Offor, P. O. (2021). Experimental Effect of Filler Variation on the polarizability of polymer Matrix Composites Developed from Orange Peel Particulates . *Journal(of(Materials(and(Environmental(Science*, *12*(3), 406–417.

Pradhan, K. K., & Chakraverty, S. (2019). *Computational Structural Mechanics Static and Dynamic Behaviors* (Vol. 20, Issue 5). Academic Press.

Prokopchuk, A., Zozulia, I., Didenko, Y., Tatarchuk, D., Heuer, H., & Poplavko, Y. (2021). Dielectric permittivity model for polymer–filler composite materials by the example of Ni-and graphite-filled composites for high-frequency absorbing coatings. *Coatings*, *11*(2), 1–20.

Qu, J., & Wong, C. P. (2002). Effective elastic modulus of underfill material for flip-chip applications. *IEEE Transactions on Components and Packaging Technologies*, *25*(1), 53–55.

Rahmani, K., & Majzoobi, G. H. (2019). The effect of particle size on microstructure, relative density and indentation load of Mg-B4C composites fabricated at different loading rates. *Journal of Composite Materials*, *54*(17), 2297–2311.

Rajesh, S., Murali, K. P., & Ratheesh, R. (2009). Preparation and Characterization of High Permittivity and Low Loss PTFE/CaTiO3 Microwave Laminates. *Polymer Composites*, *30*, 1480–1485.

Raju, G. G. (2017). *Dielectrics in Electric Fields* (2nd ed.). CRS Press.

Ratheesh, R., & Sebastian, M. T. (2017). Polymer–Ceramic Composites for Microwave Applications. In M. T. Sebastian, R. Ubic, & H. Jantunen (Eds.), *Microwave Materials and Applications* (pp. 481–527). John Wiley & Sons, Ltd.

Rayssi, C., El Kossi, S., Dhahri, J., & Khirouni, K. (2018). Frequency and temperature-dependence of dielectric permittivity and electric modulus studies of the solid solution Ca0.85Er0.1Ti1-: XCo4 x /3O3 (0 ≤ x ≤ 0.1). *RSC Advances*, *8*(31), 17139–17150.

Ren, J., Bi, K., Fu, X., & Peng, Z. (2018). Novel Al2Mo3O12-based temperature-stable microwave dielectric ceramics for LTCC applications. *Journal of Materials Chemistry C*, *6*(42), 11465–11470.

Ren, J., Yang, P., Peng, Z., & Fu, X. (2021). Novel Al2Mo3O12-PTFE composites for microwave dielectric substrates. *Ceramics International*, *47*(15), 20867–20874.

Sabarinathan, P., Annamalai, V. E., Rajkumar, K., & Vishal, K. (2021). Effects of recovered brown alumina filler loading on mechanical, hygrothermal and thermal properties of glass fiber–reinforced epoxy polymer composite. *Polymers and Polymer Composites*, *29*(9_suppl), S1092–S1102.

Sachin, K. O., Maruthi, B. H., Puttaswamaiah, S., & Satish, B. (2021). Effect of fillers on water and chemical absorption behavior of natural fiber reinforced epoxy composites. *International Journal of Biosensors & Bioelectronics*, *7*(3), 69–72.

Saparuddin, D. I., Zaid, M. H. M., Ab Aziz, S. H., & Matori, K. A. (2020). Reuse of eggshell waste and recycled glass in the fabrication porous glass-ceramics. *Applied Sciences (Switzerland)*, *10*(16).

Sasikala, T. S., & Sebastian, M. T. (2016). Mechanical, thermal and microwave dielectric properties of Mg2SiO4 filled Polyteterafluoroethylene composites. *Ceramics International*, *42*(6), 7551–7563.

Schindelin, J., Rueden, C. T., Hiner, M. C., & Eliceiri, K. W. (2015). The ImageJ ecosystem: An open platform for biomedical image analysis. *Molecular Reproduction and Development*, *82*(7–8), 518–529.

Shamsuddin, M. S. M., Nasir, R. M., Hassan, A., & Ishak, Z. A. M. (2020). Mechanical and tribological properties of solid lubricant (PTFE) filled carbon fiber reinforced polycarbonate composites. *AIP Conference Proceedings*, *2267*(September).

Shannon, R. D. (1993). Dielectric polarizabilities of ions in oxides and fluorides. *Journal of Applied Physics*, *73*(1), 348–366.

Shao, S., Tian, Y., Zhou, H., Song, Y., Lian, H., Wu, H., … Xie, Q. (2020). Effect of morphology and particle size of bismuth ferrite filler on the surface insulation of epoxy resin composites. *Polymer Composites*, *41*(11), 4514–4525.

Shao, Y., Yang, J. J., & Huang, M. (2016). A review of computational electromagnetic methods for graphene modeling. *International Journal of Antennas and Propagation*, *2016*.

Sheen, N. I., & Woodhead, I. M. (1999). An open-ended coaxial probe for broad-band permittivity measurement of agricultural products. *Journal of Agricultural and Engineering Research*, *74*(2), 193–202.

Snyder, A. W., & Love, J. D. (1983). *Optical Waveguide Theory*. Chapman and Hall.

Solyom, K., Lopez, P. R., Esquivel, P., Lucia, A., & Vásquez-Caicedo. (2020). Effect of temperature and moisture contents on dielectric properties at 2.45 GHz of fruit and vegetable processing by-products. *RSC Advances*, *10*(28), 16783–16790.

Sood, B., & Pecht, M. (2011). Controlling moisture in printed circuit boards. *IPC*

APEX EXPO Technical Conference 2011, *1*, 1–53.

Struchkova, T. S., Vasilev, A. P., Alekseev, A. G., Okhlopkova, A. A., & Danilova, S. N. (2022). Mechanical and Tribological Properties of Polytetrafluoroethylene Composites Modified by Carbon Fibers and Zeolite. *Lubricants*, *10*(1).

Sun, J., Jiang, B., Li, W., Cheng, X., Liu, H., & Li, Z. (2022). Study on the Microstructure and Mechanical Properties of Diamond Particle-Reinforced Copper-Iron Sandwich Composites Prepared by Powder Metallurgy. *Materials*, *15*(2424), 1–13.

Tan, Y., Liu, Y., Yan, X., Lu, G., Xie, K., Tong, J., & Meng, F. (2022). Functionalized Al2O3 fillers/glass fibers cloth/PTFE composites with excellent thermal properties. *Journal of Materials Science: Materials in Electronics*, *33*, 8815–8821.

Tan, Y., Yan, X., Tang, C., Lu, G., Xie, K., Tong, J., & Meng, F. (2021). Dielectric and thermal properties of GFs/PTFE composites with hybrid fillers of Al2O3 and hBN for microwave substrate applications. *Journal of Materials Science: Materials in Electronics*, 23325–23332.

Tang, T., Yuan, Y., Yalikun, Y., Hosokawa, Y., Li, M., & Tanaka, Y. (2021). Glass based micro total analysis systems: Materials, fabrication methods, and applications. *Sensors and Actuators, B: Chemical*, *339*(March), 129859.

Ternero, F., Rosa, L. G., Urban, P., Montes, J. M., & Cuevas, F. G. (2021). Influence of the total porosity on the properties of sintered materials—a review. *Metals*, *11*(730), 1–21.

Thomas, S., Kavil, J., & Mathew Malayil, A. (2016). Dielectric properties of PTFE loaded with micro- and nano-Sm2Si2O7 ceramics. *Journal of Materials Science: Materials in Electronics*, *27*(9), 9780–9788.

Van Der Wel, P. (1999). Powder mixing. In *Powder Handling and Processing* (Vol. 11, Issue 1).

Varghese, J., Nair, D. R., Mohanan, P., & Sebastian, M. T. (2015). Dielectric, thermal and mechanical properties of zirconium silicate reinforced high density polyethylene composites for antenna applications. *Physical Chemistry Chemical Physics*, *17*(22), 14943–14950.

Vartak, D., Ghotekar, Y., Deshpande, N., Munjal, B. S., Bhatt, P., Satyanarayana, B., … Lal, A. K. (2021). New horizons of Space Qualification of Single-Walled Carbon Nano Tubes-Carbon Fibre Reinforced Polymer Composite. *Journal of Physics: Conference Series*, *1854*(1).

Venables, H. J., & Wells, J. I. (2001). Powder mixing. *Drug Development and Industrial Pharmacy*, *27*(7), 599–612.

Venkatesh, M. (2002). *Integrated Dual Frequency Permittivity Analyser using*

Cavity Perturbation Concept. (Unpublished doctoral thesis). McGill University.

Venkateswarlu, G., Sharada, R., Rao, M. B., Junior, T., Girls, C., & Karimnagar, D. (2015). Effect of fillers on mechanical properties of PTFE based composites. *Archives of Applied Science Research*, *7*(7), 48–58.

Vilchevskaya, E. N., & Müller, W. H. (2021). Modeling of orientational polarization within the framework of extended micropolar theory. *Continuum Mechanics and Thermodynamics*, *33*(4), 1263–1279.

Wahab, R. A. A., Mohammad, M., Mazlan, M., Razali, M. A. M., Rusni, N. A. M., Sharisun Asma, W. A. N., … Zaid, M. H. M. (2021). Physical properties of low energy consumption fired industrial waste-clay bricks from cockle shells and soda lime silica glass. *AIP Conference Proceedings*, *2332*(March).

Wang, H, Zhou, F., Guo, J., Yang, H., Tong, J., & Zhang, Q. (2020). Modified BCZN particles filled PTFE composites with high dielectric constant and low loss for microwave substrate applications. *Ceramics International*, *46*(6), 7531–7540.

Wang, Hao, Zhou, F., Guo, J., Zhang, Y., Yang, H., & Zhang, Q. (2020). Surface-modified Zn0.5Ti0.5NbO4 particles filled polytetrafluoroethylene composite with extremely low dielectric loss and stable temperature dependence. *Journal of Advanced Ceramics*, *9*(6), 726–738.

Wang, J., Lim, E. G., Leach, M. P., Wang, Z., & Man, K. L. (2020). Open-ended coaxial cable selection for measurement of liquid dielectric properties via the reflection method. *Mathematical Problems in Engineering*, *2020*.

Wang, X., & Tretyakov, S. A. (2022). Fast and Robust Characterization of Lossy Dielectric Slabs Using Rectangular Waveguides. *IEEE Transactions on Microwave Theory and Techniques*, *70*(4), 2341–2350.

Wang, Y., Jiang, C., & Wang, Z. (2021). Effect of sintering factors on properties of Al-rich PTFE/Al/TiH2 active materials. *Polymers*, *13*(11).

Warnick, K. F. (2020). *Numerical Methods for Engineering* (2nd ed.). The Institution of Engineering and Technology.

Wu, B., Xu, Y., & Tang, X. (2021). Improved dielectric and mechanical properties of polyolefin based laminates via surface modification silicon dioxide. *IOP Conference Series: Earth and Environmental Science*, *639*(1).

Xie, C., Liang, F., Ma, M., Chen, X., Lu, W., & Jia, Y. (2017). Microstructure and dielectric properties of PTFE-based composites filled by micron/submicron-blended CCTO. *Crystals*, *7*(5).

Xie, J., Li, H., Sang, X., Zhang, H., & Chang, A. (2022). Effect of filler content on the dielectric properties of Ba1-xVxTiO3/PVDF composite flexible films. *Materials Letters*, *316*(February), 132057.

Xue, P. J., Liu, S. L., & Bian, J. J. (2021). Effects of polymorphic form and particle size of SiO2fillers on the properties of SiO2-PEEK composites. *Journal of Advanced Dielectrics*, *11*(4), 1–8.

Yakubu, A., Abbas, Z., & Abdullahi, S. (2020). Mechanical, Dielectric and Shielding Performance of Rice Husk/Polycaprolactone Composites Enhanced via Rice Husk Particles Inclusion. *OALib*, *07*(07), 1–12.

Yakubu, A., Abbas, Z., & Sirajo, A. (2020). Attenuation and Shielding Performance of Wood-Polymer Composites Synthesized via Melt-Blend Technique. *OALib*, *07*(02), 1–11.

Yamada, Y. (2022). Dielectric Properties of Textile Materials: Analytical Approximations and Experimental Measurements—A Review. *Textiles*, *2*(1), 50–80.

Yamaguchi, A., Kido, H., Ukita, Y., Kishihara, M., & Utsumi, Y. (2016). Anisotropic pyrochemical microetching of poly(tetrafluoroethylene) initiated by synchrotron radiation-induced scission of molecule bonds. *Applied Physics Letters*, *108*(5).

Yang, Jie, Zhu, X., Wang, H., Wang, X., Hao, C., Fan, R., … Shi, Z. (2020). Achieving excellent dielectric performance in polymer composites with ultralow filler loadings via constructing hollow-structured filler frameworks. *Composites Part A: Applied Science and Manufacturing*, *131*(February), 105814.

Yang, Junyi, Tang, Z., Yin, H., Liu, Y., Wang, L., Tang, H., & Li, Y. (2019). Poly(arylene ether nitrile) Composites with Surface-Hydroxylated Calcium Copper Titanate Particles for High-Temperature-Resistant Dielectric Applications. *Polymers*, *11*(5).

Yuan, Y., Lin, H., Jiang, Z., Chi, Z., Yao, M., & Zhang, S. (2017). Effects of Content of Chopped Glass Fibers on the Properties of Silica Filled PTFE Composites. *Journal of Materials Science and Chemical Engineering*, *05*(07), 36–44.

Zhang, F., Zhang, J., Zhu, Y., Wang, X., & Jin, Y. (2020). Microstructure and properties of polytetrafluoroethylene composites modified by carbon materials and aramid fibers. *Coatings*, *10*(11), 1–20.

Zhang, K., Zhao, D., Chen, W., Zheng, L., Yao, L., Qiu, Y., & Xu, F. (2022). Three-dimensional woven structural glass fiber/polytetrafluoroethylene (PTFE) composite antenna with superb integrity and electromagnetic performance. *Composite Structures*, *281*(2022), 115096.

Zhang, Ke, Ji, X., Mi, Y., Gao, L., & Wang, T. (2021). Effects of carbon fibers with different particle sizes on the physical properties of MoS2-filled PTFE composites. *Philosophical Magazine Letters*, *101*(7), 277–286.

Zhang, L., Qiao, Q., Yue, Z., Yang, F., & Li, L. (2015). A new HDPE/BST polymer-ceramic composite for wireless temperature sensing. *Ceramics*

International, *41*(S1), S471–S475.

Zhang, Y., Lv, X., Zhang, Y., Jiang, Z., & Gong, C. (2021). Tunable microwave absorbing property of RGO/Fe3O4/SiO2nanocomposites by effective regulation of eddy current effect. *Journal of Applied Physics*, *130*(17).

Zhou, S., Deng, R., Wang, B., Weng, Z., Luo, H., & Wang, X. (2020). Preparation and microwave dielectric properties of PTFE Composites Filled with Rutile Particles/Fibers. *2020 21st International Conference on Electronic Packaging Technology, ICEPT 2020*.

Zhu, X., Feng, S., Rao, Y., Ju, S., Zhong, Z., & Xing, W. (2022). A novel semi-dry method for rapidly synthesis ZnO nanorods on SiO2@PTFE nanofiber membrane for efficient air cleaning. *Journal of Membrane Science*, *645*(November 2021), 120206.

Zou, C., Fothergill, J. C., & Rowe, S. W. (2008). The effect of water absorption on the dielectric properties of epoxy nanocomposites. *IEEE Transactions on Dielectrics and Electrical Insulation*, *15*(1), 106–117.