JOURNAL OF SCIENCE
SAKARYA UNIVERSITY

Sakarya University Journal of Science

ISSN 1301-4048 | e-ISSN 2147-835X | Period Bimonthly | Founded: 1997 | Publisher Sakarya University | http://www.saujs.sakarya.edu.tr/en/

Title: Mechanical and Electrical Response of Structural Capacitor for Various Dielectric Materials

Authors: Aysun EĞRİSÖĞÜT TİRYAKİ, Oğuzhan Bartuğ KURUKAYA
Recieved: 2019-11-12 11:36:28

Accepted: 2020-04-08 15:16:22

Article Type: Research Article
Volume: 24
Issue: 3
Month: June
Year: 2020
Pages: 555-563

How to cite
Aysun EĞRİSÖĞÜT TİRYAKİ, Oğuzhan Bartuğ KURUKAYA; (2020), Mechanical and Electrical Response of Structural Capacitor for Various Dielectric Materials. Sakarya University Journal of Science, 24(3), 555-563, DOI: https://doi.org/10.16984/saufenbilder.645408
Access link
http://www.saujs.sakarya.edu.tr/en/issue/52472/645408

Sakarya University Journal of Science 24(3), 555-563, 2020

Mechanical and Electrical Response of Structural Capacitor for Various Dielectric Materials

Aysun EĞRİSÖĞÜT TİRYAKİ*[1], Oğuzhan Bartuğ KURUKAYA[1]

Abstract

Due to the run out of the fossil energy sources and environmental issues, new energy storage systems are developed in conjunction with renewable energy technologies. The machines that supplied energy from the batteries consume extra energy because they carry both the weight of the batteries and the structural weight. Recently, the idea of storing energy in structural elements has been studied. In this study, the multifunctionality of structural capacitors made by placed of varied dielectric layers between the carbon fiber plates has been investigated. The effects on the mechanical and electrical properties of different dielectric material combinations has been investigated by the simulation, experimentally and by the calculations based on Hook's law. Thus, the results of structural dielectric capacitors in these combinations have been compared and discussed.

Keywords: Structural capacitor, energy storage, multifunctional composites, dielectric materials.

1. INTRODUCTION

The materials that can give a functional response to environmental changes or stimulating external influences are called Smart Materials. These materials are affected by electromagnetic field, light, pressure, humidity, temperature, power. Smart materials can perform more than two tasks at the same time. This is called multifunctionality. The composite materials used in energy storage mechanism are also multifunctional materials just like them. Multifunctional energy storage composites represent a novel form of multifunctional structural battery materials that can carry mechanical loads while simultaneously providing energy-storage capabilities [1]. By placing dielectric film between these materials, structural capacitors are obtained that function as energy storage capacitors. O'Brien at all [2] calculated to multifunctionality and built structural capacitor. In his work, he found specific mechanical properties such as specific stiffness etc. Also, O'Brien et al. [3] showed that electrode materials and processing method have a significant effect on performance. Tony Carlson and al. [4,5] used three different surface weights

*Corresponding Author: aysune@sakarya.edu.tr ; ORCID: https://orcid.org/0000-0001-6440-8396.
[1]Sakarya University, Department of Mechanical Engineering, Sakarya, Turkey.

of paper and three different polymer films (Polyamide-PA, Polyethylene Terephthalate-PET and Polycarbonate-PC) as a dielectric layers in his work and characterized multifunctional performance of the structural capacitor by measuring capacitance, dielectric strength and interlaminar shear strength. Shen and Zhou [6] studied the effects of delamination and interlaminar damage on the mechanical and electrical performance of carbon-fiber structural capacitor (CFSC) materials. Chan and al. [7,8] developed the multifunctional structural dielectric capacitor by using carbon fiber reinforced composites and graphene oxide paper and showed that the electrical and mechanical properties of the this new structural dielectric capacitors were significantly enhanced. Chan and al. [9] added gold nanoparticles into the epoxy matrix of carbon fibre reinforced polymer based electrodes used in graphene oxide-bearing structural dielectric capacitors in his later work and provided improving both the electrical and mechanical properties of the capacitor. Ladpli and al. proposed and analyzed the multifunctional energy storage composite structures that encapsulated lithium-ion battery materials inside high-strength carbon-fiber composites [1].

In this study, the structural dielectric capacitors have been manufactured by using of paper, Polyvinyl Chloride (PVC) and Polytetrafluoroethylene (PTFE) film as dielectric material between reinforced carbon fiber plates. Mechanical and electrical properties of these capacitors have been studied experimentally, by simulation and calculation and obtained results are compared.

2. THEORETICAL MODEL

2.1. Mechanical Properties of Carbon Fiber Reinforced Polymer (CFRP) Matrix

Carbon fiber reinforced polymer matrix materials are consist of a combination of one or more carbon fiber layer to make a heterogeneous material with polymer matrix. The layer formed by the polymer matrix with single layer carbon fiber is called lamina. The structure that many layers come together is called laminate. Lamina and laminate are shown in Figure 1.

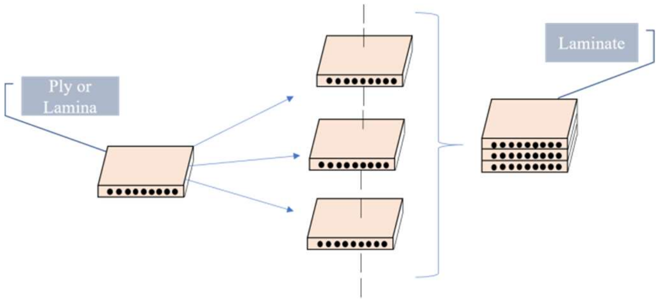


Figure 1. Lamina and laminate

CFRP is generally anisotropic, i.e. it exhibits different mechanical properties in different directions. The calculation of the mechanical properties of the laminate [10] is shown in equation (1).

$$\begin{bmatrix} N_x \\ N_y \\ N_{xy} \\ M_x \\ M_y \\ M_{xy} \end{bmatrix} = \begin{bmatrix} A_{11} & A_{22} & A_{16} & B_{11} & B_{12} & B_{16} \\ A_{12} & A_{22} & A_{26} & B_{12} & B_{22} & B_{26} \\ A_{16} & A_{26} & A_{66} & B_{16} & B_{26} & B_{66} \\ B_{11} & B_{12} & B_{16} & D_{11} & D_{12} & D_{26} \\ B_{12} & B_{22} & B_{26} & D_{12} & D_{22} & D_{26} \\ B_{16} & B_{26} & B_{66} & D_{16} & D_{26} & D_{66} \end{bmatrix} \begin{bmatrix} \varepsilon_x^0 \\ \varepsilon_y^0 \\ \gamma_{xy}^0 \\ \kappa_x \\ \kappa_y \\ \kappa_{xy} \end{bmatrix} \quad (1)$$

$$A_{ij} = \sum_{k=1}^{n} [(\bar{Q}_{ij})]_k (h_k - h_{k-1}), i = 1,2,6; j = 1,2,6 \quad (2)$$

$$B_{ij} = \frac{1}{2} \sum_{k=1}^{n} [(\bar{Q}_{ij})]_k (h^2{}_k - h^2{}_{k-1}), i = 1,2,6; j = 1,2,6 \quad (3)$$

$$D_{ij} = \frac{1}{3} \sum_{k=1}^{n} [(\bar{Q}_{ij})]_k (h^3{}_k - h^3{}_{k-1}), i = 1,2,6; j = 1,2,6 \quad (4)$$

2.2. Carbon Fiber Composite Capacitor

The capacitor is a device for storing electrical charge or electrical energy in an electrical field. In its simplest form a capacitor consist of two metal plates separated by a dielectric layer, as shown in Figure 2 [11].

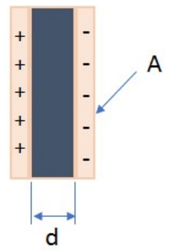


Figure 2. Parallel plate capacitor

The ability of a capacitor to store a charge on its conductive plates gives it its Capacitance value and is calculated as:

$$C = \frac{\varepsilon_r \times \varepsilon_0 \times A}{d} \tag{5}$$

where C is capacitance, A is plate area, d is separation distance of the plates, ε_0 is permittivity of space and ε_r is the relative permittivity of the dielectric material.

A composite capacitor is formed by placing a dielectric separator between two carbon fiber laminae. As can be seen in Figure 3, two carbon fiber laminae numbered 2 are placed in front of and behind a dielectric separator.

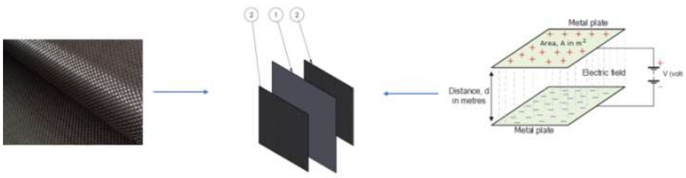


Figure 3. Structure of carbon fiber capacitor

To investigate mechanical and electrical performance of dielectric materials in the structural capacitor, the representative properties should be selected. While tensile testing for mechanical properties the capacitance and hence electrical energy density were measured for electrical performance.

2.3. Energy Density

The energy density is the amount of energy stored per mass. The maximum energy storage is calculated based on the dielectric strength voltage. The energy density [4] is calculated as follows eq. (6).

$$\bar{\Gamma} = \frac{\frac{1}{2} C V^2}{m_{sc}} \tag{6}$$

In this formula $\bar{\Gamma}$ is energy density, C is capacitance, V is dielectric strength voltage of dielectric material and m_{SC} is mass of the structural capacitor.

3. MANUFACTURING OF ENERGY STORAGE STRUCTURE

3.1. Vacuum Bagging Method

In this study is used vacuum bagging method for molding. Figure 4 shows Vacuum Bagging Method. The sample is prepared on a metal mold. Dielectric material is placed between the wet carbon fiber plate pair. There is a separating cloth and glass wool layer on top of this structure, respectively. Finally, vacuum is applied by covering the vacuum bag.

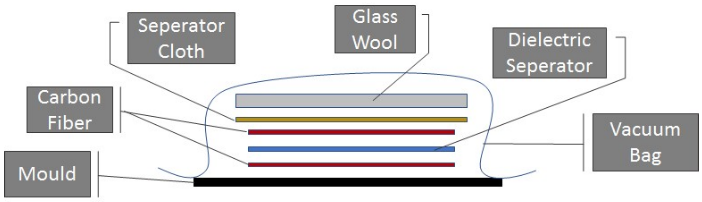


Figure 4. Vacuum Bagging Method

The materials used in the vacuum bag method are illustrated in Figure 5 and Figure 6 shows the vacuum application.

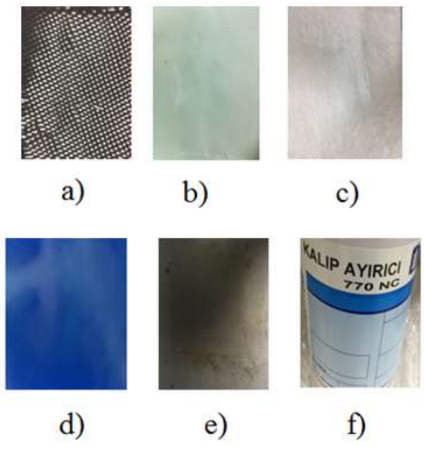


Figure 5. Vacuum bagging materials (a-Carbon fiber, b-Separator cloth, c-Glass wool, d-Vacuum bag, e-Metal mold, f-770 NC mold separator)

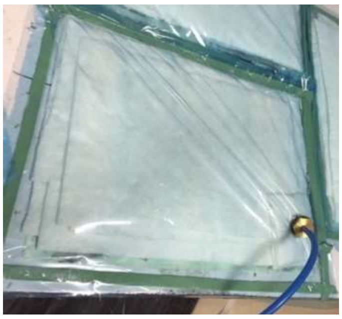


Figure 6. Vacuum bag application

3.2. Product and Features

Five samples containing various dielectric materials were produced by vacuum bag method for electrical test. These test samples are shown in Figure 7, respectively 80 microns PVC (ETS1), 120 micron PVC (ETS2), 80 micron PTFE (ETS3), 120 micron PTFE (ETS4) and 100 micron paper (ETS5). The electrical test specimens were formed by inserting 100 x 100 mm carbon fiber laminate in the center of the 130 x 130 mm dielectric material.

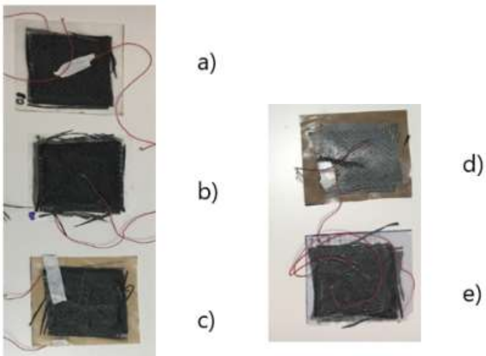


Figure7. Electrical Test Specimens (a-ETS1, b-ETS2, c-ETS3, d-ETS4, e-ETS5)

In addition, each dielectric-carbon fiber pair was produced in accordance with ASTM D3039 standards to perform mechanical tests. These mechanical test specimens were produced with 80 micron PVC (MTS1), 120 micron PVC (MTS2), 80 micron PTFE (MTS3), 120 micron PTFE (MTS4), paper (MTS5) and only carbon fiber (MTS6). Mechanical test specimens produced according to ASTM D3039 standards are shown in Figure 8. However, as seen in Figure 8 e-f, the mechanical test specimens made with PTFE test specimens were separated into pieces when cut.

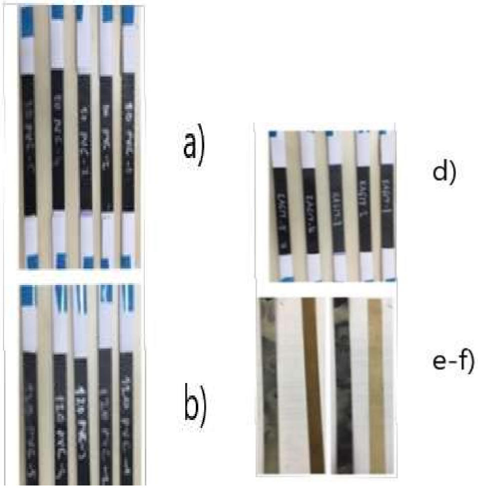


Figure 8. Mechanical Test Specimens (a-MTS1, b-MTS2, c-MTS6, d-MTS5, e-f-MTS3-MTS4)

4. MODELING AND SIMULATIONS

4.1. 3D Plain Model

The 3D plain model (Figure 9) was created using TexGen geometric modelling scheme developed by the University of Nottingham. 3x3 yarn, 1.75mm yarn spacing, 1.5mm yarn width and 0.25mm fabric thickness were used in model.

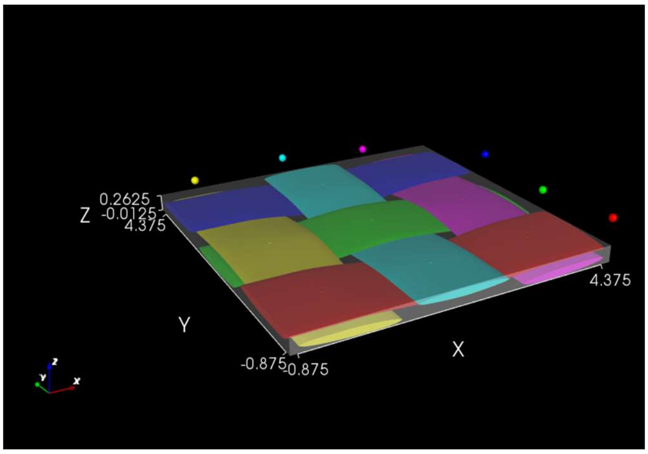


Figure 9. Geometric model of 3x3 unit cell

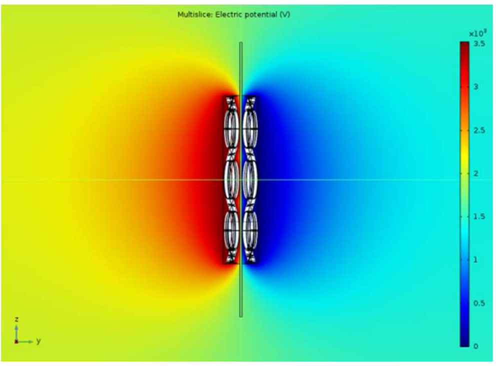
4.2. Electrostatic Simulation

The electric field and capacitance are solved under electrostatic conditions. Electrostatic simulations were performed for models obtained using different dielectric materials in this study. In simulation, 90% of the dielectric strength voltage of each insulator material was applied. The dielectric strength voltages of the materials and applied voltages in the simulation are shown on the Table 1.

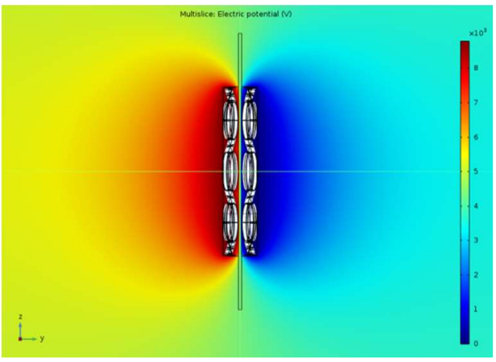
Table 1. Applied voltages in electrostatic simulation

	Applied Voltage[V]	Dielectric Strength Voltage [kV/mm]
ETS1(80pvc)	3528	3920
ETS2(120pvc)	8794,8	9772
ETS3(80ptfe)	2304	2560
ETS4(120ptfe)	3456	3840
ETS5(paper)	1440	1600

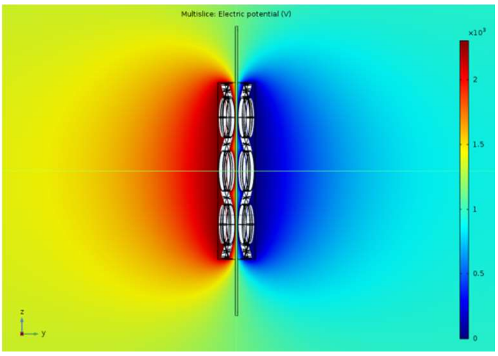
Figure 10 shows electric potentials applied to ETS1, ETS2, ETS3, ETS4 and ETS5 test specimens. In these simulations, the effects of matrix material are neglected. The electric field results obtained from the simulations are shown in Figure 11.



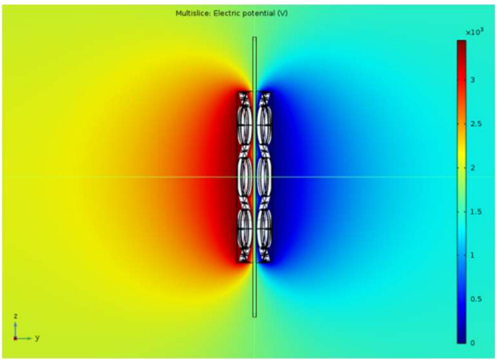
(a)



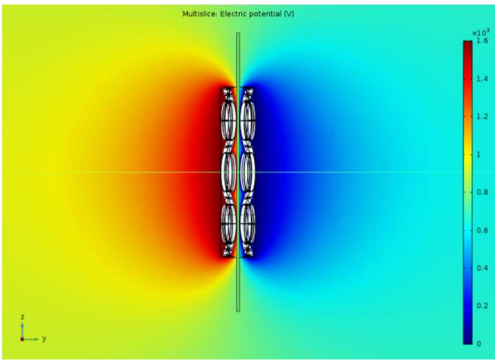
(b)



(c)

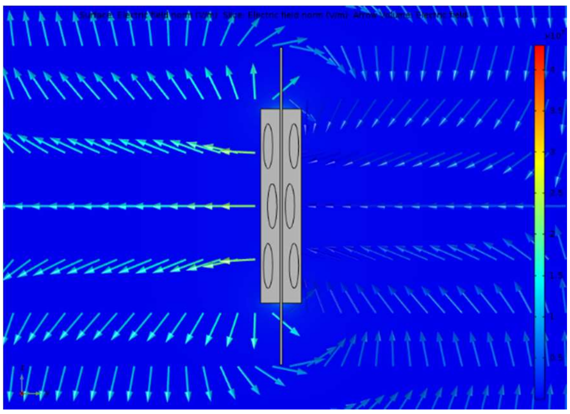


(d)

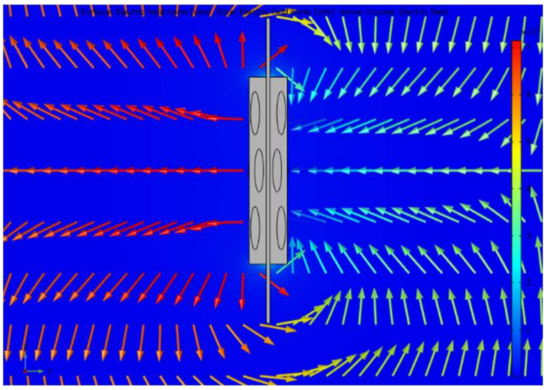


(e)

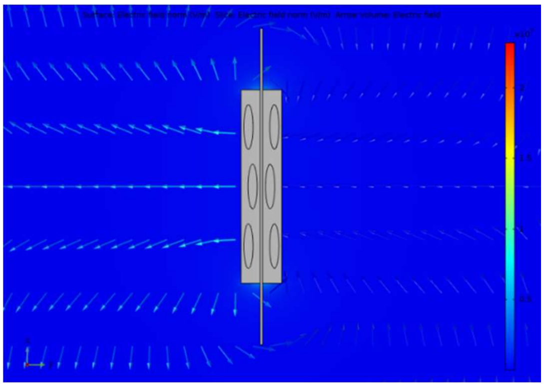
Figure 10. Electric potentials applied in electrostatic simulations (a-ETS1, b-ETS2, c-ETS3, d-ETS4 and e-ETS5)



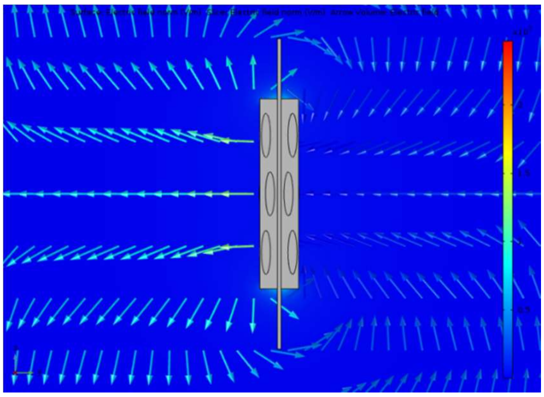
(a)



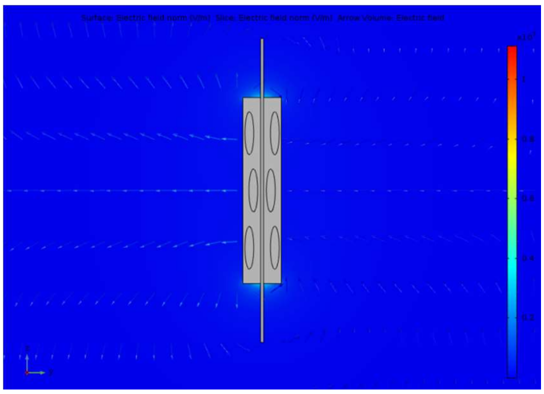
(b)



(c)



(d)



(e)

Figure 11. Electric fields obtained from simulations (a-ETS1, b-ETS2, c-ETS3, d-ETS4 and e-ETS5)

The highest value of electric field is obtained with voltage of applied 8794,8 V to PVC material. In addition to being the strongest electric field in PVC material, there is increase in the electric field with increase in the loading.

Electric Potential, as seen in the graphs, the carbon fiber surface has not spread properly due to its wavy structure. Due to the fluctuating nature of the surfaces, the distance d varies. Therefore, the carbon fiber plate capacitor stored less energy than a normal flat surface capacitor.

5. RESULTS AND CONCLUSION

Each specimen was tested five times under the same conditions for the sake of repeatability. Table 2 shows the mean test results and calculated mechanical properties. The mean tensile strength and stiffness test values were calculated by using ordinary least squares method. In addition, Hook's Law was used to calculate the mechanical properties.

Table 2. Mechanical Test Results and Calculated Mechanical Properties (E is Stiffness, v is Poisson Ratio, S is Tensile Strength)

	Calculated		Test Results		
	E[GPa]	**v**	**E[GPa]**	**v**	**S[MPa]**
MTS1	64.50	0.42	47.20	0.45	419
MTS2	65.77	0.41	61.40	0.41	528
MTS5	64.53	0.40	63.10	0.30	605
MTS6	-	-	62.97	0.43	514

TABLE 3 shows the dielectric strength of the specimens, measured capacitance values and capacitance results obtained from the simulations.

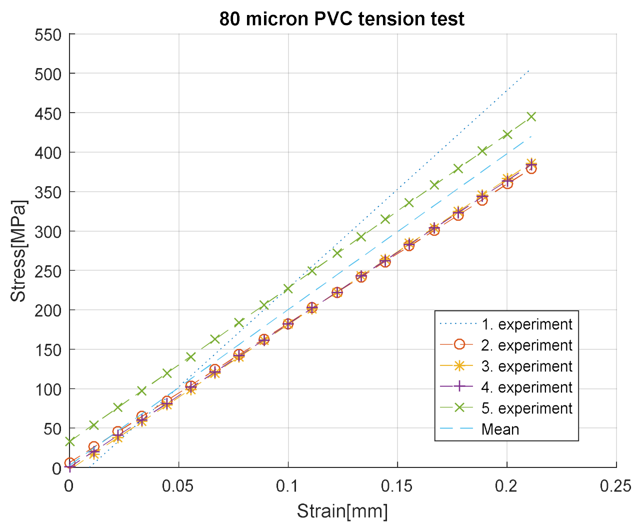
Table 3. Dielectric Strength Simulation's Capacitance Results and Measured Capacitances of Electrical Test Specimens

Specimen	Dielectric Strength[kV/mm]	Measured C[nF/m2]	Simulation C[nF/m2]
ETS1	3920	130	129,19
ETS2	9772	118	100,82
ETS3	2560	67	97,53
ETS4	3840	85	78,95
ETS5	1600	460,59	241,4

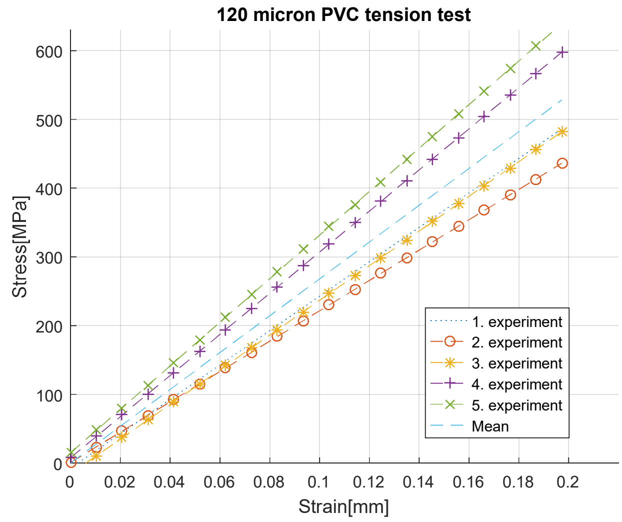
The difference between the electrostatic simulation results and the measurements is caused by the epoxy layer formed between the fibers. The accumulation of epoxy between the thin film and the carbon fiber surface increases the insulating strength of the structural capacitor and provide it to be charged with more electricity. Furthermore, the epoxy that is irregularly cured forms different insulation coefficients in different regions. Especially paper, because it absorbs epoxies, a new hybrid dielectric material is formed.

Electric fields show irregularities as shown in Figure 11. This is because a carbon fiber fabric surface has a wavy structure. If there was a flat plate, there would be a more regular electric field and a higher capacity electric storage feature. This surface ripple affects the capacity feature negatively.

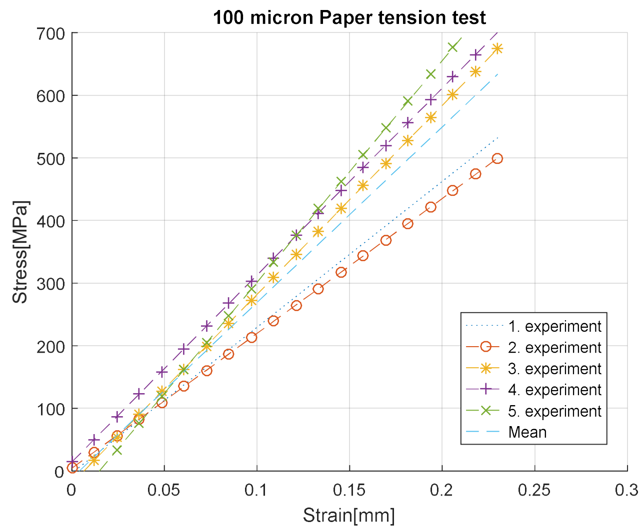
The strain-stress graphs of the mechanical test specimens are shown in Figure 12. When the strain-stress graphs are examined, it is clearly evident that the mechanical test sample containing paper dielectric material shows high mechanical performance.



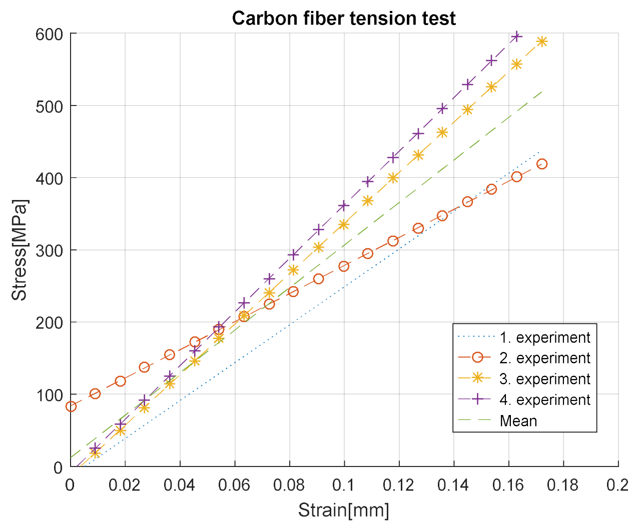
(a)



(b)



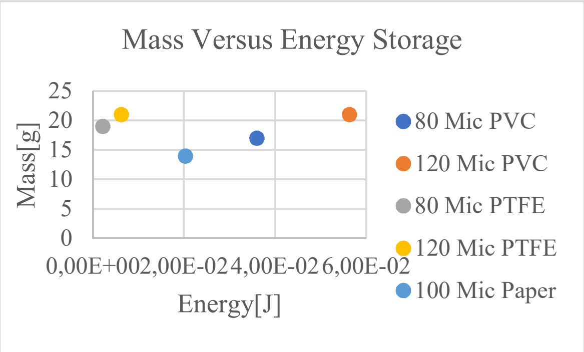
(c)



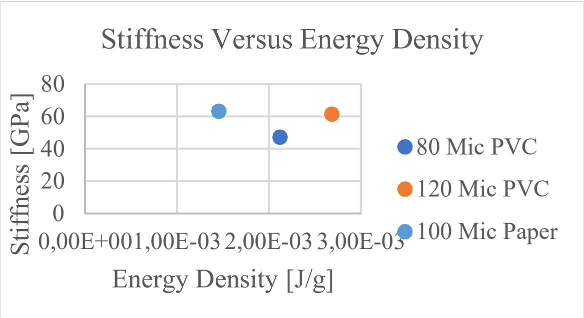
(d)

Figure 12. Tensile Test Results (a-MTS1, b-MTS2, c-MTS5 and d-MTS6)

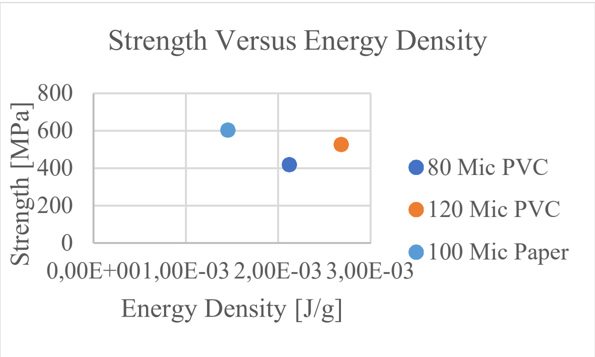
The multifunctionality of structural capacitors made by placed of varied dielectric layers between the carbon fiber plates were compared in Figure 13. It is seen in Figure 13.a that the capacitor that stores the most energy is ETS2. Figures 13.b and c show that the capacitor that stores the most energy density with high stiffness and strength is also ETS2.



(a)



(b)



(c)

Figure 13. For the structural capacitors with various dielectric materials: a-Mass Versus Energy Storage, b-Stiffness Versus Energy Density, c-Strength Versus Energy Density

In the study, the capacitor made of PTFE has been found to have very low mechanical properties despite the energy storage. As previously predicted and as can be also seen in the tests carried out the layer formed between the PTFE separator layer and the carbon fiber did not adhere to each other. That's why, using of this pair in structural capacitors is not recommended because it tends to break apart.

The paper made capacitor showed both higher energy storage and higher mechanical properties than the others. Paper-containing carbon fiber capacitor has a better adhesion surface with epoxy than other dielectric materials. This has affected the electrical and mechanical properties positively. But due to its low dielectric strength, it has less energy storage capability than PVC.

Better mechanical and capacitive properties of the 120 micron PVC-made capacitor may be associated with better adhesion to carbon fiber. In terms of energy density, 120 micron PVC provides higher capacity. The main reason for this is that the insulation strength is higher than other thin films, and combinations with this film can be loaded at higher voltages.

As a result manufacturing defects and the failure to adhere well to the dielectric materials of carbon fiber affect mechanical and electrical properties of the capacitor. Thin films with low adhesion energy have a negative effect on the system in terms of both mechanical properties and capacity.

In addition, another factor that increases the capacity, and accordingly, the energy density of the structural capacitor is the accumulation of epoxy between the thin film and the carbon fiber surface. This accumulation will increase the insulating resistance of the structural capacitor and it will provide that loaded it with more electricity. However, this accumulation is very difficult to measure. If epoxy accumulation is measured, its effect on mechanical properties and energy density can be discussed.

Acknowledgments

This study is supported by Sakarya University Scientific Research Projects Coordination Unit. Project Number: 2018-50-01-006.

REFERENCES

[1] P. Ladpli, R. Nardari, F. Kopsaftopoulos, F.K. Chang, "Multifunctional energy storage composite structures with embedded lithium-ion batteries," Journal of Power Sources, vol.414, pp.517-529, February 2019.

[2] D.J. O'Brien, D.M. Baechle, E.D. Wetzel, "Multifunctional structural composite capacitors for U.S. army applications," Proceedings of SAMPLE 2006, Dallas, Texas, USA, 2006.

[3] D.J. O'Brien, D.M. Baechle, O.B. Yurchak, E.D. Wetzel, "Effect of Processing Conditions and electrode characteristics on the electrical properties of structural composite capacitors," Composites Part A: Applied Science and Manufacturing, vol.68, pp.47-55, January 2015.

[4] T. Carlson, D. Ordeus, M. Wysocki, L.E. Asp, "Structural capacitor materials made from carbon fiber epoxy composites," Composite Science Technology, vol.70, no.7, pp. 1135-1140, July 2010.

[5] T. Carlson, L.E. Asp, "Structural carbon fibre composite/PET capacitors – Effects of dielectric separator thickness" Composites Part B: Engineering, vol.49, pp. 16-21, June 2013.

[6] Z. Shen and H. Zhou, "Mechanical and electrical behavior of carbon fiber structural capacitors: Effects of delamination and interlaminar damage," Composite Structures, vol.166, pp. 38-48, 2017.

[7] K.Y.Chan, B. Jia, H. Lin, B. Zhu, K.T.Lau, "Design of a structural power composite using graphene oxide as a dielectric material layer," Mater. Lett., vol.216, pp. 162-165, 2018.

[8] K.Y. Chan, H. Lin, K. Qiao, B. Jia, K.T.Lau, "Multifunctional graphene oxide paper embodied structural dielectric capacitor based on carbon fibre reinforced composites," Composite Science and Technology, vol.163, pp. 180-190, 2018.

[9] K.Y. Chan, D. Yang, B. Demir, A.P. Mouritz, H. Lin, B. Jia, K.T.Lau, "Boosting the electrical and mechanical properties of structural dielectric capacitor composites via gold nanoparticle doping," Composites Part B, vol.178, 107480, 2019.

[10] Autar K. Kaw, Mechanics of Composite Materials, Second Edition. Published in 2006 by CRC Press. International Standard Book Number-10: 0-8493-1343-0 (Hardcover).

[11] P. Jain, E.J. Rymaszewski, Rensselaer Polytechnic Institute Troy, NY, 2004. Thin-Film Capacitors for Packaged Electronics. ISBN 978-1-4419-9144-7 (eBook), DOI 10.1007/978-1-4419-9144-7.