
Synthesis and Development of Phosphazene Nano- Fiber Reinforced Composite Material for Weight Reduction in Dc Motor Body

¹SARASWATHI A, ²KANIMOZHLI K, ³RAJASEKARAN S, ⁴ROHINI G

¹⁻³Assistant Professor, ⁴Professor,
¹Department of Electrical & Electronics Engineering
^{1,3}University College of Engineering,
Villupuram

²Department of Chemistry
²University College of Engineering (BIT Campus),
Tiruchirappalli

³Department of Mechanical Engineering
Department of Electrical & Electronic Engineering,
S A Engineering College, Chennai

Email: rajasekaran.aut@gmail.com

Abstract

In the present work, a star-type epoxy terminated phosphazene nanofiber (PZE) is synthesized by reacting Hexa-chloro-cyclo-tri-phosphazene (HCCP) with 4, 4'- sulfonyl-diphenol (BPS). Further, the sonication method followed by epoxidation was used to fabricate nanofiber. With diglycidyl ether of bisphenol-A (DGEBA) and cured using 4, 4'-diaminodiphenylmethane (DDM) to obtain PZE-based nanocomposite. From the experimental results, the 1.0% PZE possesses good mechanical properties even though 1.5% PZE possesses good thermal and dielectric properties. Moreover, 1.0 wt.% PZE has suitable dielectric as well as thermal properties. This could be achieved by reducing the polarity of the resultant nanocomposite system. A rigid cross-linked network structure exists between the sulphone containing phosphazene fiber and the epoxy matrix.

Keywords: *Thermo mechanical properties, Electrical drive, Energy efficiency, Epoxy material, Nano-composites*

Introduction

Electric vehicles (EVs) are the icon of the modern industrialized world because of the high rate of fossil fuel depletion and awareness about environmental impacts. Nearly 60 % of the world's fuel consumption is merely to meet out for transportation. In this current scenario, electric vehicles are the best alternate solution for fossil fuel depletion and environmental pollution. According to the US Department of Energy, the power utilized for electric vehicles was 77%, whereas the spark ignition vehicles could only transform about 12% to 30% of gasoline energy into wheel power [1]. Moreover, the average weight of a car engine is around 158 kg. But an electric motor's weight is comparatively low and produces a high power-to-weight ratio. In general, many research challenges are addressed in the design and control of electric vehicles [2]. The electric motor was invented in the 18th century, but electric vehicles were developed in the 19th centuries. Still, in the 20th century, people are looking forward to better design and control of electric vehicles.

The electric motor is one of the main components among the many integrated parts of an EV, which is used to produce the required torque and hence replaced the internal combustion engine. There are five types of motors used in the EV drive. The various vehicle dynamics are based on acceleration, traction capacity, and ability to climb uphill depending on the efficiency of machine design. In this regard, the eco-friendly method of products is a crucial factor in the e- vehicle. Magnetic characteristics are presently specified according to DIN standard EN 10106. Mechanical strength and chemical properties may be significantly changed [3]. Optimizing products while keeping their functional attributes can create new chances for producers and customers as a preventative measure. To adhere to the global necessity of implementing steps to minimize energy consumption in all relevant sectors, the adoption of efficient, improved electric motors is essential [4]. Researchers from all around the world are working to develop lightweight materials for all sections of electric motors. Due to its high inexpensive cost and flux density, silicon steel is commonly employed in electrical devices as a magnetic element [5].

Nanocrystalline soft magnetic alloys, with less core loss, less magnetostriction, good thermal resistance, and high absorptivity, have emerged as viable alternative materials in recent years [6]. The weight distribution of each component in an electric motor is shown in Fig.1[7].

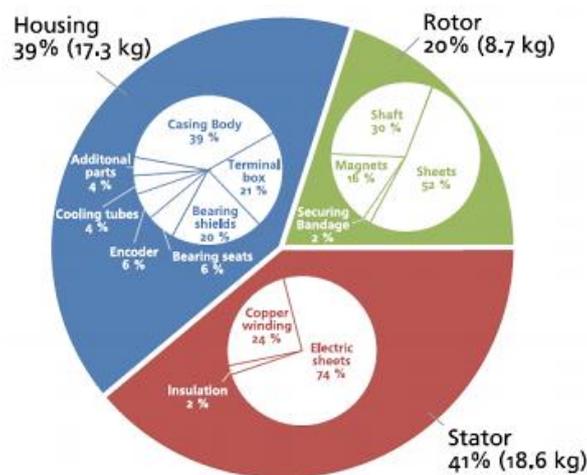


Fig. 1 Distribution of weight of an electric motor [6]

In addition to environmental compatibility, electric motors possess high torque and good driving dynamics. In recent years, the performance study of electric vehicle core materials has increased drastically [8]. Tian et al. [9] created a novel high polymer produced via phosphazene that is crystalline, opaque, and has a diverse variety of glass transition temperatures depending on the side groups and co-substituents. All of them were hydrophobic and resistant to hydrolysis [9]. Hsu et al. [10] created materials with a range of organic side groups that make them compostable and biocompatible. Based on these advantages, phosphazenes have been investigated for different biological applications, including developing many improved drug delivery applications.

Sirotin et al. [11]. Studied the functional phosphazenes' contribution not only to reduced flammability but also to be used to adjust the mechanical properties of the resulting thermosets. Zhou et al. [12] examined the characteristics of poly-phosphazenes, an organic-inorganic polymer. Whose main chain was alternating by single and double phosphorus and nitrogen links. It was provided with outstanding natural flame retardant synergy and thermal stability. The cross-linked cycle structures were created to increase the overall qualities of materials, particularly the flame-resistant capabilities, thermal stability, and mechanical properties. In recent years, nano material-related technologies and micromechanical systems have obtained many applications in science and engineering, especially in electric vehicles. In the present work, the study has been made on a non-material and explores its electric and mechanical characteristics.

Experiment work

Preparation of nano- particles

Hexa-chloro-cyclo-tri-phosphazene (HCCP) and 4, 4' - sulfonyldiphenol (BPS) was prepared using standard practice. Epichlorohydrin, sodium hydroxide, 4, 4' - diaminodiphenylmethane (DDM) were added to enhance the nanocomposite's mechanical and thermal properties. Further, Sulphone containing phosphazene nanofiber and epoxy-group terminated phosphazene were synthesized according to the procedure reported [20]. The synthesis of Sulphone containing phosphazene nanofiber reinforced epoxy composites was involved two steps as follows as.

Step 1: Synthesis of semi-inorganic sulphone - containing phosphazene nanofibre (PZS)

Initially, 14.4 grams of BPS was mixed with 300 ml of THF and sonicated for 10 min. Further, 12 ml of TEA was added and sonicated for 20 min. Although, 5 g of HCCP and 200 ml of THF were added and sonicated for 5 hr. The finished product underwent three rounds of filtering and washing with THF and deionized water. The purified material was then dried in hot air. The material sulphone encapsulating phosphazene nanofibers was produced as an 82 percent white powder.

Step 2: Synthesis of epoxy-group terminated phosphazene (PZE)

In addition, 0.3 g of phosphazene nano-fiber-containing sulphone was added to 50 mL THF in a 100 mL flask. For 10 minutes, the mixture was immersed in an ultrasonic bath (240 W, 80 kHz). The flask was then filled with epichlorohydrin with 9 g (7.6 ml). The solution temperature was increased to 60° C before adding 4 ml of 3 percent NaOH dropwise and remaining at 60° C for 5 hours. The solid product was rinsed with distilled water and ethanol, then dried in a vacuum chamber. Figure 2 depicts the synthetic process for creating epoxy terminated phosphazene.

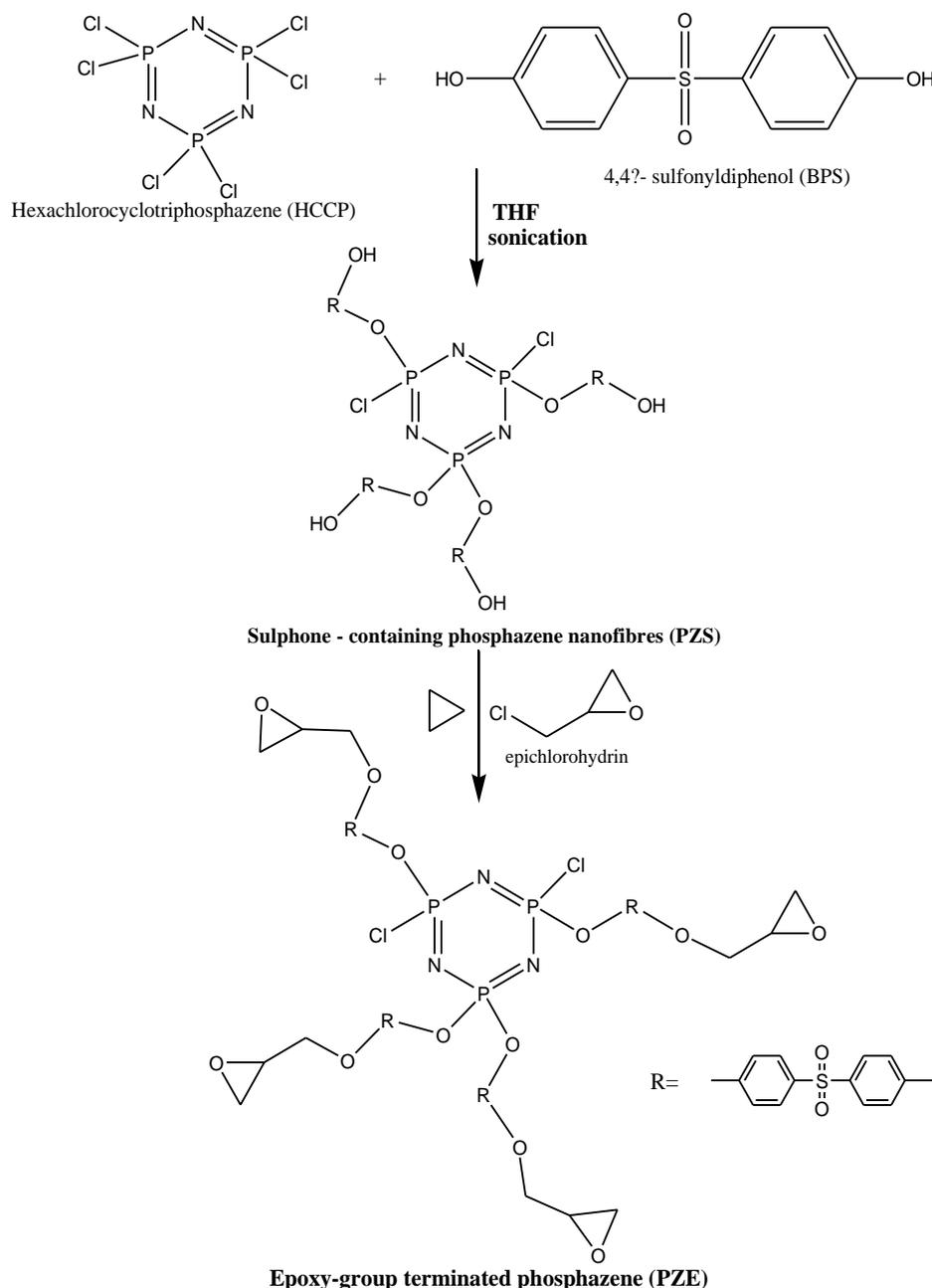


Fig.2 Scheme for Synthesis of PZE Nano fiber

Preparation of the PZE nano-composites

The epoxy resin (LY556) and epoxy-group terminated PZE were mixed in a predetermined ratio of 40/0.2, 40/0.4, and 40/0.6. By weight obtained, phosphazene-based epoxy blends are referred to as 0.5% PZE, 1.0% PZE, and 1.5% PZE, respectively. Each blend sample was agitated separately using a mechanical stirrer for 24 hrs. Until a uniform dispersion is achieved, add a stoichiometric quantity of 4,4'-diaminodiphenylmethane as a cure. The consistent mix was put into the mold and cured at 120 degrees Celsius for 2 hours

and 180 degrees Celsius for 3 hours. Finally, the mold was extracted from the mold and analyzed using several techniques.

Characterization method

The FT-IR spectra of the nanocomposite were measured using a Perkin Elmer spectrometer. Calorific value measurement was carried out by the scanning electron calorific meter. Thermo-gravity meter setup was used to measure the thermos-gravity analysis. The moisture absorption test of the composite was measured as per the ASTM D 570 standard. The following empirical equation was used to quantify the water absorption capacity of the nanocomposite.

$$\% \text{ Water absorption} = (W2-W1) / W1 \times 100 \quad (2)$$

W1 and W2 represent the initial and final composite weight in the water absorption test, respectively. The water absorption test was performed in distilled water for 48 hours at 25 degrees Celsius. An impedance analyzer test was used to measure the electrical behavior. A Universal Testing Machine measured nanocomposite material's tensile strength (ASTM D3039) and flexural strength (ASTM D790). An Izod impact test (ASTM D 256-88) was performed to record the energy absorption capacity. Vicker micro hardness tester (ASTM D 2240. 210) was used to measure hardness property. Contact angles were measured using a goniometer tester with 5ml of deionized water and di iodomethane. The phases of the nanocomposites were identified using an X-ray powder diffractometer. Using a scanning electron microscope showed the surface morphology of the cracked surface (after tensile testing).

Results and discussion

Evaluation of Material properties

A star-type phosphazene nanofiber was synthesized and characterized by FT-IR. The hybrid nanosized PZE fiber was reinforced with epoxy with a weight percentage of 0.5 %, 1.0 %, and 1.5 %. Incorporating PZE nano fiber up to 1.0 wt % enhances the thermomechanical behavior of the resulting nanocomposites beyond 1.0 wt %; the values are decreased. The resulting nanocomposites possess higher values of LOI (define loi), char yield, and ascertain their flame-retardant and intumescent character. The PZE nano fiber acts as an efficient nano reinforcement, influencing the enhancement of thermal stability and glass transition temperature by lowering the dielectric constant value. The hybrid PZE nanocomposites exhibit lower surface free energy and higher contact angle as a function of hydrophobicity. The developed PZE nanocomposites in this study could be used in the form of coatings, additives, sealants, and matrices for composites for a wide range of industries, especially for solar thermal applications, with improved performance and enhanced longevity.

Dielectric Properties of PZE-epoxy nanocomposites

The values of the dielectric constant (k) of neat epoxy and PZE nanocomposites are presented in Table 1. The dielectric constant for neat epoxy, 0.5 %, 1.0 % and 1.5 % PZE nanocomposites are 4.50, 3.16, 3.05 and 2.94 respectively. The dielectric constant is higher for neat epoxy and decreases with an increase from 0.5 % to 1.5 %.

Table 1 Thermal and dielectric properties of PZE nanocomposites

Sample	T _g (°C)	20% weight loss (°C)	50% weight loss (°C)	Char Yield at 700 (°C)	Water absorption (%)	Dielectric constant (MHz)	LOI 0.4×(σ) + 17.5
Neat epoxy	165	372	393	0	0.1232	4.50	20.5
0.5 % PZE	198	386	399	16.2	0.1078	2.16	23.98
1.0% PZE	201	391	416	23.2	0.0964	2.05	26.78
1.5% PZE	204	408	453	29.6	0.0520	1.94	29.34

The inter-phase strength between the inorganic reinforcement and organic domains is strongly related to the dielectric constant of the resulting nanocomposites. The dielectric constant of nanocomposites decreased with increased interaction force between the reinforcement and the matrix. The uniform and homogenous dispersion of PZE nanofiber into the matrix were observed from the X-ray diffractogram and TEM micrograph, which contributes to low 'k values' [21-23] of resulting PZE composites.

The water absorption behavior of nanocomposite samples was studied by immersing them in deionized water for 48 hrs at ambient temperature. The obtained data for neat epoxy and different weight percentages of PZE nanocomposites are shown in Table 1. Resistant to water absorption increased with an increase in the concentration of PZE due to its inherent hydrophobic behavior. The inter-cross link density of resulting PZE nanocomposites also contributes to resistance to water absorption.

Table 2: Contact angle and surface energy of PZE nanocomposites

Sample name	Contact angle in Degree		Surface Energy (N.m ⁻¹)		
	Water	Diodo-methane	γ ^d	γ ^p	Γ
PZE1	86.8	55.1	31.4	3.0	34.3
PZE2	95.8	61.5	27.7	1.3	29.0
PZE3	96.0	63.8	26.7	1.4	28.2

Table 2 shows the contact angle measurements made using a goniometer. Contact angle measures a liquid's capacity to moisten a solid surface using water and diiodo methane

as dispersive liquids. When the water contact angle is less than 90°, the surface is hydrophilic; when it is more significant than 90°, the surface becomes hydrophobic.

However, the contact angle is more than just a parameter that determines liquid-solid interactions; it also has something to do with the adherence of the liquid drop to the solid surface, which is essential when liquid sliding is involved. The contact angle of 0.5% PZE, 1.0% PZE, and 1.5% PZE were found to be 86.8°, 95.8°, and 96.0°, respectively, using 5 µl of deionized water as probe liquid. It indicates that 0.5% PZE is hydrophilic; as we increase the concentration of sulphone-containing phosphazene nanofiber, there is an increment in the hydrophobic nature. Using the diiodo methane, the dispersive liquid, the contact angle was increased to 55.1°, 61.5°, and 63.8°, respectively.

It's doesn't necessarily imply that the surface is hydrophobic; rather, it indicates that the surface structure in equilibrium with a set of ambient variables shortly before the measure is such that the contact angle of water is significant. The interaction strength parameter was proposed to include two components. The first is determined by the interactions of liquid and solid surface atoms, which are affected by the chemical makeup of both the liquid and the solid. Thus, the chemical composition induces an interaction between PZE nanofiber and epoxy matrix, indicating a less polar and hydrophobic nature of - (P-N)n- linkage in the nanocomposites.

The second factor is the amount of stress required to produce the equilibrium configuration in the liquid molecules. The latter is related to the polymer molecules' surface features and flexibility [24, 25]. The surface energy of composite surfaces may be estimated using contact angles. The geometric mean model was used to compute the surface free energy (γ) of organic-inorganic hybrid nanocomposites [20-22].

$$\cos \theta = 2/\gamma_L [(\gamma_L^d \gamma_s^d)^{1/2} + (\gamma_L^p \gamma_s^p)^{1/2}] \quad (3)$$

$$\gamma_s = \gamma_s^d + \gamma_s^p \quad (4)$$

Where L is the liquid surface tension, sd and sp are the dispersive and polar components of L, respectively, and θ is the contact angle. According to Table 2, the surface free energies of the 1.5 percent PZE included epoxy system were lower than those of other composites. This might be attributed to the successful interaction of PZE nanofiber and epoxy matrix in reducing the polarity of the resulting nanocomposite system. This higher contact angle behavior is strongly made to withstand the composites on rainy days and extend the life as an energy receiver and storage device. [26-28].

Mechanical Properties of PZE-epoxy nano composites

The values of tensile strength of PZE-epoxy nano composites are presented in Table 3. The tensile strength of neat epoxy matrix is 61.3 MPa.

Table 3: Mechanical Properties of PZE nanocomposites

Sample	Tensile strength (MPa)	Tensile modulus (MPa)	Flexural strength (MPa)	Unnotched Izod impact strength (J.m ⁻¹)	Hardness Number
Neat Epoxy	61.3	2713	106	102	84
0.5% PZE	64.9	2856	124	156	124
1.0% PZE	78.0	2894	146	188	224
1.5% PZE	66.0	2799	129	134	105

Incorporating PZE fiber into epoxy resin enhances the tensile strength value up to 1.0% wt and beyond, and it starts to decrease. The importance of tensile strength of 0.5, 1.0, and 1.5% wt PZE incorporated epoxy nanocomposites are 65, 78, and 66 MPa, respectively. The improvement in the value of tensile strength may be explained due to the existence of a rigid crosslinked network structure between the sulphone containing phosphazene fiber and the epoxy matrix. The rigid backbone resulting from the cyclo-tri-phosphazene ring and the epoxy group enhanced the crosslink density appropriately [32, 33]. When 1.5% wt of PZE nanofiber is incorporated into the epoxy matrix may lead to agglomeration and to inhomogeneous dispersion, which results in a reduction in the value of tensile strength of 66MPa. Similar trends were observed for tensile modulus.

The values of flexural strength, impact strength, and hardness of neat epoxy matrix and PZE nanocomposites (PZE) are presented in Table 3. The data infers that the reinforcement of phosphazene into epoxy matrix up to 1.0 wt% enhanced the mechanical strength and impact behavior significantly. Beyond, it lowers the values due to accumulation, as evidenced by SEM micrographs. Interestingly, both strength and energy-absorbing behavior were improved by incorporation of a small weight percentage of PZE nano fiber due to the formation of the star-type molecular structure of resulting nanocomposites, which provides rigidity with enhanced free volume within the system. [34-38] Further, the impact behavior of 1.0 wt. % PZE reinforced hybrid nanomaterials were enhanced appreciably and can be used for coating applications for better performance. The scheme of synthesis of PZE nanofiber is shown in Fig. 3a. The intensity versus transmittance of PZE and PZS are compared, shown in Fig. 3b.

The FTIR spectra of PZE composites with three different composites such as 0.5% PZE, 1.0% PZE, and 1.5% PZE. The thermal properties of PZE nanocomposite with varying proportions as shown in Fig. 4a. Also, the effect of temperature with varying ratios of weight of PZE is illustrated in Fig. 4b. Among three proportions, the 0.5 Wt.% of nanocomposite conceived higher heat flow conductivity. In contrast, lower heat flow conductivity at 1.5 wt% of PZE was observed.

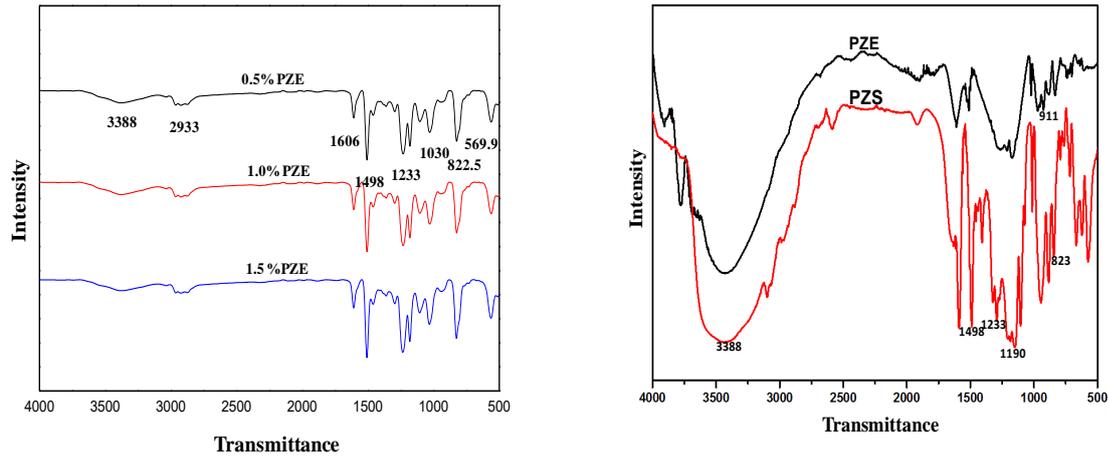


Fig.3 a) FTIR Spectra of PZE Nano composites and b) FTIR Spectra of PZS and PZE Nano fiber

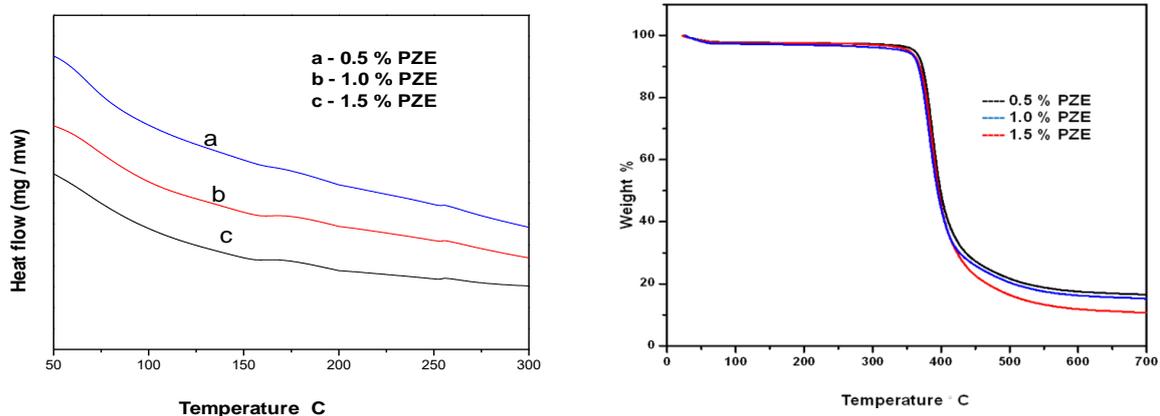


Fig. 4 a) DSC of PZE Nano composites and b) TGA of PZE Nano Composites

Conclusion

The experimental study involved the design of lightweight composite material for the core used in an electric motor. From the experimental results, the following inferences are derived.

- i) The 1.0% PZE possesses good mechanical properties. Even though 1.5% PZE has good thermal and dielectric properties, 1.0% PZE possesses better mechanical properties with suitable dielectric and thermal properties.
- ii) The mechanical strength and thermal properties are suitable for core material selection. In the future, this 1.0% PZE composite material can be used to develop the required core material of the electric drive.

iii) Compared to its equivalent, a 1.5 percent PZE integrated epoxy system had a reduced interfacial energy value. It might be attributed to the effective interaction of PZE nanofiber and epoxy matrix in reducing the polarity of the resulting nanocomposite system.

iv) The tensile strength of 0.5, 1.0, and 1.5% wt PZE incorporated epoxy nanocomposites are 65MPa, 78MPa, and 66 MPa, respectively. The improvement in tensile strength may be explained due to the existence of a rigid cross-linked network structure between the sulphone containing phosphazene fiber and the epoxy matrix.

v) The reinforcement of PZE into epoxy matrix up to 1.0 wt% enhanced the mechanical strength and impact behavior significantly and beyond. It lowers the values due to accumulation.

vi) Both strength and energy-absorbing behavior were improved by incorporating a small weight percentage of PZE nano fiber due to the formation of the star-type molecular structure of resulting nanocomposites, providing rigidity with enhanced free volume within the system.

Scope of future work

- i) The practical limitation will explore under various working conditions.
- ii) Based on the experimental results and viability study, this nanocomposite may also be used for fabricating the motor body.

REFERENCES

1. Zhang XH, Huang LH, Cen S, Qi GR: Improvement of thermal properties and flame retardancy of epoxy-amine thermosets by introducing bisphenol containing azomethine moiety, EXPRESS Polymer Letters 1 (2007), No.5, pp. 326–332, DOI:10.3144/expresspolymlett.2007.46
2. Lu SY, Hamerton I: Recent Developments in the chemistry of halogen-free flame retardant polymers, Progress in Polymer Science 27, (2002), pp. 1661–1712. DOI: 10.1016/S0079-6700(02)00018-7
3. Dustin Knetsch, Matthias Funk, Herzogenaurach, Tobias Kennerknecht, Christoph Eberl, Freiburg: Load Data Calculation in Electric Axle Drives and Fatigue Assessment for the Electric Motor Subsystem, Materials Testing 56, (2014), pp. 535 – 541, DOI: 10.3139/120.110594
4. Solomon, Darius & Greco, A. & Masselli, Claudia & Gundabattini, Edison & Rassiah, Raja Singh & Ravi, Kuppan: A Review on Methods to Reduce Weight and to Increase Efficiency of Electric Motors Using Lightweight Materials Novel Manufacturing Processes, Magnetic Materials and Cooling Methods 44, (2020), pp. 1-14 , DOI: org/10.18280/acsm.440101

5. Solomon, Darius & Gundabattini, Edison & Rassiah, Raja Singh: Materials for lightweight electric motors – a review, *IOP Conference Series: Material Science and Engineering* 906, (2020), pp.012-020, DOI: 10.1088/1757 899X/906/1/012020
6. Yifan Jia, Congyi Yang, Xueyang Chen, Wenqing Xue, Helena J. Hutchins-Crawford, Qianqian Yu, Paul D. Topham, Linge Wang: A review on electrospun magnetic nanomaterials: methods, properties and applications, *Journal of Materials Chemistry* 9, (2021), No.29, pp. 9031-9334, DOI:10.1039/D1TC01477C, (2021). Crossref
7. S Darius Gnanaraj, Edison Gundabattini and R Raja Singh, Materials for lightweight electric motors – a review, *Materials Science and Engineering* 906, (2020), pp. 1-8. DOI:10.1088/1757-899X/906/1/012020
8. Ugur Demir, Istanbul and Zeliha Kamis, Kocabicak, Bursa: Performance assessments of the material for the traction motor cores of an electric racing kart, *Materials Testing* 63, (2021), No.6, pp. 519 – 528, DOI: 10.1515/mt-2020-0085
9. Zhicheng Tian, Andrew Hess, Christopher R. Fellin, Hunaid Nulwala, and Harry R. Allcock: Phosphazene High Polymers and Models with Cyclic Aliphatic Side Groups: New Structure–Property Relationships, *Macromolecules* 48, (2015), No.13, pp. 4301–4311. DOI: org/10.1021/acs.macromol.5b00946
10. Wei-Hsin Hsu, Noemi Csaba, Cameron Alexander, Marcos Garcia-Fuentes, Polyphosphazenes for the delivery of biopharmaceuticals: *Journal of Applied Polymer Science* 137 (2019), No.25, DOI:10.1002/app.48688.
11. XiaZhou, ShuilaiQiu, XiaoweiMu, MutianZhou, WeiCai, LeiSong, WeiyiXing, YuanHu, Polyphosphazenes-based flame retardants: A review, *Composites Part B: Engineering* 202, (2020), pp. 1-17, DOI:10.1016/j.compositesb.2020.108397
12. YiqiWang, MikhailSoldatov, Qingzheng,Wang, Hongzhi Liu: Phosphazene functionalized silsesquioxane-based porous polymers for absorbing I₂, CO₂ and dyes, *Polymer* 218, (2021), No.18, pp. 491-518. DOI:org/10.1016/j.polymer.2021.123491
13. Hayrettin Gokozan, Mehmet Tastan, Sezai Taskin, Pinar Sari Cavdar and Ugur Cavdar: Comparison of electrical energy consumption for different material processing procedures, *Materials Testing* 58, (2016), No.6, pp. 1009 – 1013, DOI: 10.3139/120.110954
14. Zhang F, Zhang J, Wang Y: Modelling study on the combustion of intumescent fire-retardant polypropylene, *Express Polymer Letters* 1, (2007) pp. 157–165, DOI:10.3144/EXPRESSPOLYMLETT.2007.25
15. Toldy A, Tóth N, P Anna, G Marosi: Synthesis of phosphorus- based flame retardant systems and their use in an epoxy resin: *Polymer Degradation and Stability* 91, (2006), pp. 585–592, DOI: org/10.1016/j.polymdegradstab.2005.02.025
16. Jothibas S, Ashok Kumar A and Alagar M: Synthesis of maleimide substituted polystyrene–silica hybrid utilizing michael addition reaction, *Journal of Sol-Gel Science and Technology* 43, (2007), pp. 337-345, DOI:10.1007/s10971-007-1586-y

17. Ran Liu, Xiaodong Wang: Synthesis, characterization, thermal properties and flame retardancy of a novel nonflammable phosphazene-based epoxy resin, *Polymer Degradation and Stability* 94, (2009). pp. 617–624, DOI:10.1016/j.polymdegradstab.2009.01.008
18. Xiaojun Gu, Xiaobin Huang, Hao Wei, Xiaozhen Tang: Macromolecular Nanotechnology Synthesis of novel epoxy-group modified phosphazene-containing nanotube and its reinforcing effect in epoxy resin, *European Polymer Journal* 4, (2011), pp.903–910, DOI:10.1016/j.eurpolymj.2011.01.007
19. Allcock HR, Ambrosio AMA: Synthesis and characterization of pH sensitive poly (organophosphazene) hydrogels, *Biomaterials* 17, (1996), No.2, pp.295–302, DOI: 10.1016/0142-9612(96)00073-7
20. Tsai MH and Whang WT: Dynamic mechanical properties of polyimide/poly (silsesquioxane)-like hybrid films, *Journal Applied Polymer Science* 81, (2001), pp. 2500–2516, DOI: org/10.1002/app.1692
21. Allcock HR, Bender JD, Chang Y, McKenzie M, Fone MM: Controlled refractive index polymers: polyphosphazenes with chlorinated-and fluorinated-aryloxy and alkoxy side groups, *Chemical Mater* 15, (2003), pp. 473 - 477, DOI: org/10.1021/cm020912v
22. Barbera J, Bardaji M, Jimenez J, Laguna A, Martinez M P, Oriol L., Serrano J L, Zaragoza I. Columnar Mesomorphic Organizations in Cyclotriphosphazenes. *J: American Chemical Society* 127, (2005), pp. 8994-9002. DOI: org/10.1021/ja051042w
23. Elif Okutan, Gülşah Ozan Aydın, Ferda Hacivelioglu, Adem Kılıç, Saadet Kayıran Beyaz, Serkan Yeşilot: Synthesis and characterization of soluble multi-walled carbon nanotube/poly- (organophosphazene), *Composites. Polymer* 52, (2011), pp. 1241-1248, DOI: org/10.1016/j.polymer.2011.01.015
24. Greish YE, Bender JD, Lakshmi S, Brown PW, Allcock HR, Laurencin CT: Low temperature formation of hydroxyl apatite poly alkyl oxybenzoate phosphazene composites for biomedical applications, *Biomaterials* 26, (2005), No. 1, pp. 1-9, DOI: 10.1016/j.biomaterials.2004.02.016
25. Kim JK, Toti US, Song R, Sohn YS: A macromolecular prodrug of doxorubicin conjugated to a biodegradable cyclotriphosphazene bearing a tetrapeptide, *Bioorganic & Medicinal Chemistry Letters* 15, (2005), pp. 3576-3579, DOI : 10.1016/j.bmcl.2005.05.057
26. Devaraju S, Vengatesan M R and Alagar M: Studies on thermal and dielectric properties of ether linked cyclohexyl diamine (ELCD)-based polyimide POSS nanocomposites (POSS-PI), *High Performance Polymers* 23, (2011), pp. 99-111, DOI: org/10.1177/0954008310391825
27. Liu YL, Hsiue GH, Lee RH: Phosphorous containing epoxy for flame retardant: using phosphorylated diamines as curing agents, *Journal of Applied Polymer Science* 63, (1997), pp. 895–901, DOI: 10.1002/(SICI)1097-4628(19970214)63:7<895::AID-APP9>3.0.CO;2-L

28. Devaraju S, Vengatesan MR, Selvi M, Ashok Kumar A and Alagar M: Synthesis and characterization of bisphenol - A ether diamine-based polyimide POSS nanocomposites for low K dielectric and flame-retardant applications, *High Performance Polymers* 24, (2012), pp. 85-96, DOI: [org/10.1177/0954008311433606](https://doi.org/10.1177/0954008311433606)
29. Vengatesan MR, Devaraju S, Dinakaran K and Alagar M: SBA-15 filled polybenzoxazine nanocomposites for low-k dielectric applications, *Journal of Material Chemistry* 22, (2012), No. 15, pp. 7559- 7566, DOI: [10.1039/c2jm16566j](https://doi.org/10.1039/c2jm16566j)
30. Calum J. Drummond, and Derek YC, Langmuir. Chan. van der Waals Interaction: Surface Free Energies, and Contact Angles. *Dispersive Polymers and Liquids* 13, (1997), pp. 3890-3895, DOI: [org/10.1021/la962131c](https://doi.org/10.1021/la962131c)
31. Rios PF, Dodiuk H, Kenig S, Mccarthy S and Dotan A: The effect of polymer surface on the wetting and adhesion of liquid systems. *Journal of Adhesion Science Technology* 21, (2012), pp. 227–241, DOI: [10.1163/156856107780684567](https://doi.org/10.1163/156856107780684567)
32. Wang L, Zhang C and Zheng S: Organic-inorganic poly (hydroxyether of bisphenol A) copolymers with double-decker silsesquioxane in the main chains, *Journal of Material Chemistry* 21, (2011), No. 48, pp. 19344 – 19352, DOI: [10.1039/C1JM13596A](https://doi.org/10.1039/C1JM13596A)
33. Ya-Ni Guo, Jin-Jun Qiu, He-Qing Tang, Cheng-Mei Liu: High Transmittance and Environment-Friendly Flame-Resistant Optical Resins Based on Poly (methyl methacrylate) and Cyclotriphosphazene Derivatives, *Journal of Applied Polymer Science* 121,(2011), pp.727–734, DOI: [org/10.1002/app.33806](https://doi.org/10.1002/app.33806).
34. Mandhakini M, Chandramohan A, Vengatesan MR, and Alagar M: Synthesis and characterization of linseed vinyl ester fatty amide-modified epoxy layered silicate nanocomposites, *High Performance Polymers* 23, (2011), No. 5, pp. 403–412, DOI: [10.1177/0954008311415441](https://doi.org/10.1177/0954008311415441)
35. Jianwei Fu, Xiaobin Huang, Yawen Huang, Lu Zhu, Yan Zhu, Xiaozhen Tang: Facile Preparation of Branched Phosphazene-Containing Nanotubes via an in situ Template Approach. *Macromol, Material Engineering* 293, (2008), No.3, pp. 173-177, DOI: [10.1002/mame.200700318](https://doi.org/10.1002/mame.200700318)
36. Jiawei Zhanga, Xiaobin Huang, Jianwei Fua, Yawen Huang, Wei Liua, Xiaozhen Tang: Novel PEO-based composite solid polymer electrolytes incorporated with active inorganic–organic hybrid polyphosphazene microspheres. *Materials Chemistry and Physics* 121, (2010), pp. 511–518, DOI: [org/10.1016/j.matchemphys.2010.02.016](https://doi.org/10.1016/j.matchemphys.2010.02.016)
37. Singh A, Krogman NR, Sethuraman S, Nair LS, Sturgeon JL, Brown PW, Laurencin CT, Allcock HR: Effect of Side Group Chemistry on the Properties of Biodegradable L-Alanine Cosubstituted Polyphosphazenes. *Biomacromolecules* 7, (2006), pp. 914-918, DOI: [org/10.1021/bm050752r](https://doi.org/10.1021/bm050752r)
38. Carriedo GA, Alonso FJG, Elipe PG, Brillas E, Labarta A, Julia L. Macromolecular polyradicals with cyclotriphosphazenes as a core spectral and electro chemical properties. *The Journal of Organic Chemistry* 69, (2004), No.1, pp. 69-99, DOI: [10.1021/jo035349u](https://doi.org/10.1021/jo035349u)