Hybrid Glass/Kevlar Fiber Reinforced Phenolic Matrix Composites: Thermal degradation and Flammability studies

Senthilkumar Krishnasamy[1,*], R. Sasikumar[2], G. Swaminathan[1], M. Thirukumaran[3], M. Hema[4], Jyotishkumar Parameswaranpillai[5], T. Senthil Muthu Kumar[6], D. Aravind[7], M. Chandrasekar[8], Varagunapandiyan Natarajan[9]

[1]Department of Mechanical Engineering, PSG Institute of Technology and Applied Research, Coimbatore – 641062, Tamil Nadu, India.

[2]Department of Chemistry, PSG Institute of Technology and Applied Research,

Coimbatore – 641062, Tamil Nadu, India.

[3]Department of Mechanical and Automation Engineering, PSN College of Engineering and Technology, Tirunelveli– 627 152, Tamil Nadu, India.

[4]Department of Physics, Kamaraj College of Engineering and Technology, K.Vellakulam,

Near Virudhunagar - 625 701, Tamilnadu, India.

[5]AU – Sophisticated Testing and Instrumentation Center, Alliance University, Chandapura-Anekal Main Road, Bangalore, 562106, Karnataka, India.

[6]Department of Mechanical Engineering, Kalasalingam Academy of Research and Education, Krishnankoil – 626126, Tamil Nadu, India.

[7]University Science Instrumentation Centre, Madurai Kamaraj University, Palkalai Nagar, Madurai – 625021, Tamil Nadu, India.

[8]School of Aeronautical Sciences, Hindustan Institute of Technology & Science, Padur, Kelambakkam, Chennai – 603103, Tamil Nadu, India.

[9] Department of Chemical Engineering, King Khalid University, Abha, Saudi Arabia

Corresponding author: Senthilkumar Krishnasamy, Email id: kmsenthilkumar@gmail.com

Abstract

In the present work, bio-based phenolic matrix composites (PMCs) were fabricated by reinforcing them with bi-directional glass fiber mats, bi-directional Kevlar fiber mats, and their hybrid combinations. Both fiber mats were treated with (3-glycidyloxypropyl) trimethoxysilane (GPTMS) to enhance fiber-to-matrix adhesion. Subsequently, the fibers were coated with a phenolic binder made from a mixture of phenol-hexamine-based novolac (N) resin and cardanol-hexamine-based benzoxazine (Bz) resin. Then the layers of binder-coated fibers were compressed using a hot press moulding machine at 200^{o}C to cure the resins. The developed composites were subjected to thermogravimetric analysis (TGA) and UL-94V flammability test. The glass fiber (GF-NBz) and Kevlar fiber (KF-NBz) reinforced PMCs show an overall mass loss of ~18.5% and 66% at 850^{o}C. Whereas the hybrid GF/KF fiber-reinforced PMCs exhibit balanced properties of improved thermal stability and higher char yield. The flammability test results show both pure and hybrid samples exhibited a V-0 rating. Based on these observations, the combination of glass fiber and Kevlar fiber-reinforced PMCs may be suitable for automotive applications, such as dashboards, and door panels, with improved performance and fire safety.

Highlights:

- Glass and Kevlar/phenolic and their hybrids were developed using hot press.
- Fibers coated by (3-glycidyloxypropyl) trimethoxysilane to enhance bonding.
- GF/KF composites exhibited balanced properties in thermal property.
- The pure and hybrid samples achieved a V-0 rating under UL-94V test.

Keywords: Phenolic matrix composites, thermogravimetric analysis, UL-94 test, flammability performance, and hybrid composites.

1. Introduction

Presently, the usage of fiber reinforced composites (FRCs) is increasingly used in many industrial applications due to their excellent mechanical properties, manufacturability, and durability [1]. Amongst the FRCs, Kevlar-fiber-reinforced, and glass-fiber-reinforced composites are preferred in most applications due to their advantages such as strength-to-weight ratio and superior impact resistance [2, 3]. Additionally, incorporating a phenolic matrix within these fibers can enhance flame-retardant properties, making these composites suitable

for high temperature applications in aerospace, marine, automotive, and construction industries [4].

Phenolic resin-based composites reinforced with synthetic fibers show improved properties, such as mechanical strength, thermal stability, and low thermal conductivity and making them suitable for structural and insulation purposes in industries with demanding applications [5]. Glass fiber/novolac-type phenolic resin/polyamide composites show enhanced flame-retardant properties. The researchers reported that the fabricated composites exhibited a V-0 rating in the UL-94 test, demonstrating their ability to self-extinguish quickly after exposure to fire. This combination improved both the mechanical strength and flame-retardant performance of the material [6].

The carbon fiber-reinforced composites were found to possess improved fire resistance properties due to the use of a modified epoxy binder containing triglycidyl phosphate. This modification not only enhanced the fire resistance but also resulted in improved mechanical properties. These characteristics make the modified epoxy and carbon fiber combination particularly suitable for applications requiring both stronger fire resistance and superior mechanical properties [7].

Ferdous et al. reported that adding glass fibers into phenolic matrix composites enhanced the mechanical strength and structural integrity. Moreover, adding 50% ceram powder to the composite raised the glass transition temperature (T_g) by 32°C, significantly enhancing the composite temperature resistance. These combined properties made glass fiber, phenolic resin, and ceram powder composites particularly well-suited for applications that demand superior mechanical and thermal performance in high-temperature environments [8].

Flax/carbon/Kevlar/epoxy matrix composites were found to exhibit enhanced mechanical and thermal properties, with carbon and Kevlar fibers contributing to increased thermal stability compared to pure flax fiber composites. The stacking sequence of carbon fiber/flax fiber showed a higher T_g than pure flax fiber composites. The hybrid composites, particularly those incorporating carbon fibers, were deemed suitable for lightweight engineering applications [9]. Similarly, basalt fiber/aramid fiber/carbon fiber/epoxy matrix composites demonstrated enhanced thermal stability compared to single-fiber-reinforced composites [10].

Although numerous experimental studies have been conducted on glass fiber and Kevlar fiber-reinforced composites, the potential of hybridizing these two fibers within a phenolic matrix remains underexplored. Combining glass and Kevlar fibers could lead to a unique composite

10. Karacor B, Ozcanli M (2022) Thermal and mechanical characteristic investigation of the hybridization of basalt fiber with aramid fiber and carbon fiber. Polym Compos 43:8529–8544

11. Sathishkumar TP, Satheeshkumar S, Naveen J (2014) Glass fiber-reinforced polymer composites–a review. Journal of reinforced plastics and composites 33:1258–1275

12. Chinnasamy V, Subramani SP, Palaniappan SK, et al (2020) Characterization on thermal properties of glass fiber and kevlar fiber with modified epoxy hybrid composites. Journal of materials research and technology 9:3158–3167

13. Joshua JJ, Singh D, Vennelakanti SHK, et al (2023) Fabrication and Experimental Estimation of Mechanical Properties of Kevlar-Glass/Epoxy Interwoven Composite Laminate. J Nanomater 2023:1055071

14. Jeyaguru S, Thiagamani SMK, Krishnasamy S, et al (2024) Experimental investigation on the thermal characteristics of Kevlar/hemp intraply hybrid composites: Influence of various weaving designs. Ind Crops Prod 221:119280

15. Aravind D, Krishnasamy S, Rajini N, et al (2024) Thermal and tensile properties of 3D printed ABS-glass fibre, ABS-glass fibre-carbon fibre hybrid composites made by novel hybrid manufacturing technique. Journal of Thermoplastic Composite Materials 37:206–225

16. Horadam W, Venkat N, Tran T, et al (2018) Leaching studies on Novolac resin-coated proppants-performance, stability, product safety, and environmental health considerations. J Appl Polym Sci 135:. https://doi.org/10.1002/app.45845

17. Oliveira JR, de Freitas DB, de Oliveira JFR, et al (2021) New opportunity for sustainable benzoxazine synthesis: A straight and convenient one-pot protocol for formaldehyde-free bio-based polymers. Eur Polym J 156:. https://doi.org/10.1016/j.eurpolymj.2021.110596

18. Asim M, Paridah MT, Chandrasekar M, et al (2020) Thermal stability of natural fibers and their polymer composites. Iranian Polymer Journal 29:625–648

19. Nurazzi NM, Asyraf MRM, Rayung M, et al Thermogravimetric analysis properties of cellulosic natural fiber polymer composites: A review on influence of chemical treatments., 2021, 13, 2710. DOI: https://doi org/103390/polym13162710

20. Chen Y, Fan D, Qin T, Chu F (2014) Thermal degradation and stability of accelerated-curing phenol-formaldehyde resin. Bioresources 9:4063–4075

21. Feng S, Yuan Z, Leitch M, Xu CC (2015) Thermal degradation performance of bark based phenol formaldehyde adhesives. J Anal Appl Pyrolysis 115:184–193

22. Kandasamy V, Subramanian A, Subramanian S, Rajendran S (2024) Mechano-chemical upcycling of pultruded composite waste for reuse in concrete mixture. Matéria (Rio de Janeiro) 29:e20240348

23. Banea MD, Neto JSS, Cavalcanti DKK (2022) Thermal analysis of hybrid epoxy/synthetic/natural fiber composites. In: Handbook of Epoxy/Fiber Composites. Springer, pp 903–934

24. Reis PNB, Silva MP, Santos P, et al (2021) Effect of hostile solutions on the residual fatigue life of kevlar/epoxy composites after impact loading. Molecules 26:5520

25. Barra G, Guadagno L, Raimondo M, et al (2023) A comprehensive review on the thermal stability assessment of polymers and composites for aeronautics and space applications. Polymers (Basel) 15:3786

26. Li J, Xu S, Liu Y, Cao S (2024) Luminescent/Temperature-Sensing Properties of Multifunctional Rare-Earth Upconversion Kevlar Nanofiber Composite under 1550 nm. Nanomaterials 14:740

27. Özmen FK, Üreyen ME, Koparal AS (2020) Cleaner production of flame-retardant-glass reinforced epoxy resin composite for aviation and reducing smoke toxicity. J Clean Prod 276:124065

28. Rafiee M, Nitzsche F, Laliberte J, et al (2019) Thermal properties of doubly reinforced fiberglass/epoxy composites with graphene nanoplatelets, graphene oxide and reduced-graphene oxide. Compos B Eng 164:1–9

29. Sheinbaum M, Sheinbaum L, Weizman O, et al (2019) Toughening and enhancing mechanical and thermal properties of adhesives and glass-fiber reinforced epoxy composites by brominated epoxy. Compos B Eng 165:604–612

30. Rakhman A, Diharjo K, Raharjo WW, et al (2022) Improvement of fire resistance and mechanical properties of Glass Fiber Reinforced Plastic (GFRP) composite prepared

from combination of active nano filler of modified pumice and commercial active fillers. Polymers (Basel) 15:51

31. Brown JR, Ennis BC (1977) Thermal analysis of Nomex® and Kevlar® fibers. Textile Research Journal 47:62–66

32. Azwa ZN, Yousif BF (2013) Characteristics of kenaf fibre/epoxy composites subjected to thermal degradation. Polym Degrad Stab 98:2752–2759

33. Ravindran L, MS S, Kumar S A, Thomas S (2022) A comprehensive review on phenol-formaldehyde resin-based composites and foams. Polym Compos 43:8602–8621

34. Poljansek I, Krajnc M (2005) Characterization of phenol-formaldehyde prepolymer resins by in line FT-IR spectroscopy. Acta Chim Slov 52:238

35. Sałasińska K, Celiński M, Mizera K, et al (2021) Moisture Resistance, Thermal Stability and Fire Behavior of Unsaturated Polyester Resin Modified with L-histidinium Dihydrogen Phosphate-Phosphoric Acid. Molecules 26:932

36. Li R, Zeng S, Shen K, et al (2023) Effects of mechanical grinding on the physicochemical properties of silica aerogels. Front Mater 10:1225481

37. Lu S, Shen B, Chen X (2021) Construction of charring-functional polyheptanazine towards improvements in flame retardants of polyurethane. Molecules 26:340

38. Liu H, Hahn SH, Ren M, et al (2020) Searching for correlations between vibrational spectral features and structural parameters of silicate glass network. Journal of the American Ceramic Society 103:3575–3589

39. Akibul Islam M, Chowdhury MA, Arefin Kowser M, et al (2022) Enhancement of thermal properties of Kevlar 29 coated by SiC and TiO2 nanoparticles and their binding energy analysis. Arab. J Chem 15:103959