Journal of Mines, Metals and Fuels, *73(5): 1193-1202; 2025. DOI: 10.18311/jmmf/2025/48107*

Print ISSN : 0022-2755

Journal of Mines, Metals and Fuels

Contents available at: *www.informaticsjournals.co.in/index.php/jmmf*

Synthesis and Mechanical Characterization of Pineapple Leaf Fibers and Boron Carbide Fillers Reinforced Lapox L-12 Epoxy Composites

Anitha S. H. Devi[1]*, Ghanashyam H. Shenoy[1], V. Auradi[2] and Sunil Kumar Shetty[3]

[1]Department of Mechanical Engineering, Dr. T. Thimmaiah Institute of Technology, Kolar Gold Fields - 563120, Karnataka, India; anithaphd02@gmail.com

[2]Department of Mechanical Engineering, Siddaganga Institute of Technology, Tumkur - 572103, Karnataka, India

[3]Department of Mechanical Engineering, Nitte (Deemed to be University), NMAM Institute of Technology, Karkala - 574110, Karnataka, India

Abstract

To address the growing need for composites in fields such as medicine, transportation, safety, and athletics, researchers are consistently innovating new composite materials. This work involved the preparation of Lapox L-12 epoxy composites, incorporating a fixed 40 wt. % of pineapple leaf fibres and varying boron carbide fillers at 5, 10, and 15 wt. %, utilising the hand layup method. The mechanical properties of the synthesised composites were assessed in accordance with ASTM standards, including hardness, ultimate, yield strength, elongation, and flexural strength. The use of pineapple leaf fibres and boron carbide fillers into epoxy Lapox L-12 led to improved hardness, tensile strength, and flexural strength, with a slight decrease in elongation. Lapox L-12 composites with 40 wt. % of PALF and 15 wt. % of B4C fillers demonstrated improvements of 51.6 % in hardness, 61.7% in ultimate strength, and 34.6 % in flexural strength.

Major Findings: *The experiment investigated with different weight percentage of B4C fillers and a constant weight percentage of pineapple leaf fibres. Hence the results demonstrate an improvement in the tensile strength, improved ultimate and yield strength as well as improved flexural strength and hardness, when compared to epoxy without reinforcement.*

Keywords: *Boron Carbide Fillers, Epoxy L-12, Flexural Strength, Pineapple Leaf Fibers, Tensile Strength*

1.0 Introduction

The only materials that meet industrial standards are composites. These materials are produced in accordance with the given characteristics. Depending on the matrix materials, composites were categorised as ceramic matrix composites, metal matrix composites, and polymer matrix composites[1-5]. All of these composites' excellent mechanical, physical, and thermal qualities make them important contributors to modern technology[6,7]. Polymer composite matrices have a high surface-to-volume ratio, are reusable, and offer improved mechanical properties and stiffness[8]. A series of smaller, homogeneous filaments are encased in a natural polymer matrix to form the polymer composite material. The purpose of polymer matrix composites is to transfer loads between the filaments and the matrix material[9,10]. Aeroplane components are the most important application for Metal Matrix Composites (MMC)[11-14], which are naturally flexible and offer improved flexibility, durability, hardness,

**Author for correspondence*

and dimensional stability[15]. Metal matrix composites are made by distributing a reinforcing material into the metal matrix[16,17]. The reinforcing area may be coated to stop a chemical contact with the matrix.

One type of composite material that falls within the ceramics category is Ceramic Matrix Composites (CMCs). They are composed of ceramic fibres that are enclosed in a ceramic matrix. Ceramic materials, such as carbon and carbon fibres, which are categorised as ceramic substances, may make up the fibres as well as the matrix. The material's fracture toughness is improved via ceramic composites.

Fibre adherence and load distribution are facilitated by the polymer composite matrix. Common polymers used in composites are elastomers, thermosetting polymers, and thermoplastic polymers. Thermosetting polymers are the most commonly used type. Thermoplastic and thermoset matrix phases will be used to identify commercial polymer matrix composites. Epoxies, vinyl esters, polyesters, bismaleimides, and polyamides are a few types of thermosetting resins. Despite the widespread use of thermosetting polyesters in fiber-reinforced plastics, epoxies and advanced composite resins currently control the industry[18].

Because of their unique mechanical qualities, reinforcements have been used in a variety of structural and mechanical applications[19,20]. The advantages of primary and secondary reinforcements are combined in hybrid polymer composites to enhance their qualities. These materials are therefore chosen as possible replacements for the parts used in the production of wind turbines, automobiles, and aeroplanes, as well as their corresponding parts. Additionally, as the fillers determine the quality of the interface between the reinforcements and matrix, adding particles as fillers to hybrid composites improves their mechanical properties[21]. The type, size, and quantity of filler particles used in hybrid polymer composites affect their mechanical characteristics[22,23].

In polymer composites, one or more fillers are added to a polymer resin matrix to achieve certain goals or requirements. Composites used in sports and aerospace applications require exceptional mechanical and thermal properties. Synthetic fibres, like as glass or carbon fibres, have historically been used to reinforce composites and add particular properties. Nevertheless, its delayed biodegradability is a drawback due to growing environmental concerns worldwide. As a result, scientists are looking into several ways to enhance or speed up polymeric composites' biodegradability. As a result, natural fibres show great promise as reinforcing fillers in elastomers, thermosets, and thermoplastics. Cost-effectiveness, sustainability, lightweight qualities, non-abrasiveness, non-hazardous nature, and—most importantly—the potential to improve the biodegradability of polymeric composites are the main benefits of using natural fibres in composites[24].

Superior strength and versatility are highlighted by the structural composites. Important properties of electronic composites include low dielectric constant, high thermal conductivity, poor electrical conductivity, and poor thermal expansion. While structural composites prioritise processability for bigger components, such panels, electronic composites place more emphasis on processability for smaller components, including coatings and isolated films. Furthermore, the matrix material needs to be supplemented by micro- and nanoparticles known as fillers in order for the composites to perform at their best[25].

Filler is a material employed to reduce the expense of the compound, modify product characteristics, and improve processing attributes[26,27]. Filler appears to be an auxiliary ingredient employed to augment volume and occupy a void. Besides the thermal and dielectric properties, the fillers were employed to improve the mechanical and tribological characteristics[28]. Due to their remarkable mechanical properties, elevated adhesive strength, and low creep, epoxy-based polymers provide extensive industrial uses for engineering materials; nonetheless, they exhibit brittleness. Consequently, inclusions have utilised varying concentrations of microfillers[29,30]. In recent years, several basic and experimental studies have been undertaken, mostly in the domain of polymer nanocomposites. Composites reinforced with nano- and microparticles are quickly advancing in the materials sector due to their enhanced mechanical properties and lower weight compared to standard materials such as aluminium and stainless steel[31,32]. Several researchers investigated various behaviours of natural fibers reinforced composites. Md. Syduzzaman *et al.*[33] studied the impact of natural fiber reinforced composites for ballistic applications. In their studies presented the various design,

performance and challenges in developing natural fiber reinforced composites or ballistic applications. Olajesu *et al.*[34] reviewed advances in natural fibers reinforced polymer, metal and ceramic composites. In their review presented production techniques of several natural fibers like plant fibers, animal fibers, and animal derived materials.

The aim of the investigations was to describe the mechanical properties of epoxy composites reinforced with boron carbide fillers and pineapple leaf fibres. This study sought to evaluate the effects of augmenting the boron carbide filler content from 5 to 15 wt. % while maintaining a constant 40 wt. % of pineapple leaf fibres on the hardness, ultimate, yield strength, elongation, and flexural strength of composites. The ceramic particles weight percentages in polymer or metal matrices can be added upto 10 to 15 wt. %. Beyond this 10 to 15 wt. % there is clustering, or agglomeration of particles occurs in the composites, this will reduce the properties. Further, as weight percentage of particles increases beyond 10 to 15 wt. %, there is decrease in the ductility of the composites[35,36].

2.0 Experimental Details

2.1 Materials

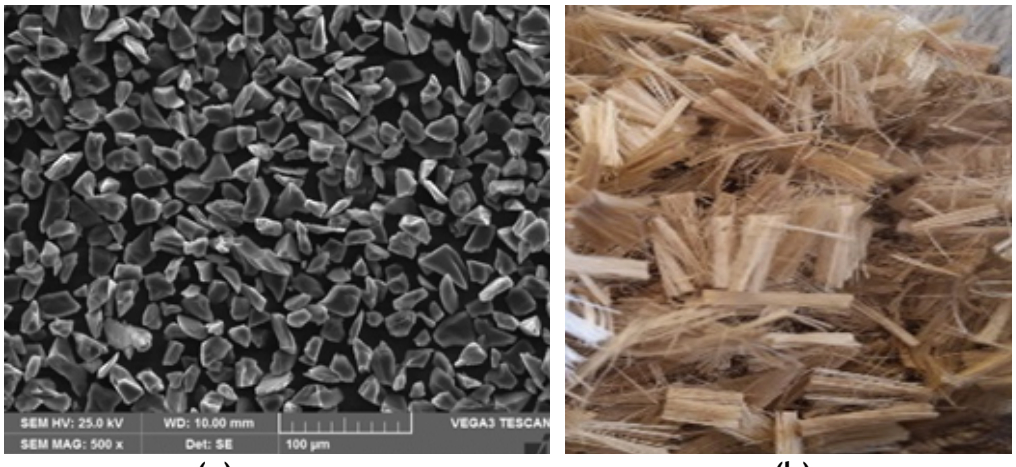
Epoxy has historically been the material of choice for epoxy composites in aerospace and automotive sectors due to its cost efficiency, exceptional strength-to-weight ratio, and processing simplicity. The epoxy matrix material employed in this study was primed at room temperature by combining epoxy L-12 and hardener K-6 in a 10:1 ratio. The epoxy polymer composites were produced utilising pineapple leaf fibres. The PAL fibres employed in this study were sourced from Bio-aid Scientific Industries Ltd., Bangalore, including chopped PALF with dimensions of 1.5 to 2 cm. The key characteristics of epoxy L-12 and PALF are delineated in Tables 1 and 2, respectively. The B_4C particles utilised in this study were acquired from Speedfam Ltd., Chennai, and exhibited a size distribution characteristic of particles within the 10–15-micron range. Table 3 presents the distinct features of B_4C fillers. Figures 1(a) and 1(b) depict the pineapple leaf fibres and boron carbide fillers utilised in the investigation.

Table 1. Mechanical Properties of Epoxy Lapox L-12

Density g/cc	Strength MPa	Young's Modulus GPa
1.2-1.3	50-125	2.5-40

Table 2. Typical properties of Pineapple Leaf Fibers

Properties	PAL Fibers
Density	1.4 to 1.5 g/cc
Tensile Strength	413-1627 MPa
Young's Modulus	34.5-82.5 GPa
Elongation at Break	1.6-3 %



(a) (b)

Figure 1. **(a)** Pineapple leaf fibers. **(b)** Boron carbide fillers.

Table 3. Typical properties of B_4C

Properties	Born Carbide
Melting Point	2450°C
Hardness	3250 kg/mm^2
Density	2.52 g/cm^3
Co-efficient of Thermal Expansion	5 x 10^{-6}°C
Fracture Toughness	3.7 MPa m$^{1/2}$
Poisson's Ratio	0.21

The hand layup technique was utilised to fabricate epoxy composites reinforced with pineapple leaf fibres and containing 5, 10, and 15 wt. % of boron carbide fillers. A combination of L-12 epoxy and K-6 hardener was initially formulated in a 10:1 ratio. Additionally, a manually operated mechanical stirrer efficiently distributed chopped fibres at a concentration of 40 wt. % in conjunction with 5 wt. % of boron carbide fillers. The epoxy composites were fabricated using open moulding technology. A mould of 300 mm x 300 mm x 3 mm, treated with a mould release agent, was employed for the fabrication of epoxy composites. The final composites were produced in a mould of 300 mm × 300 mm and 3 mm in thickness (Figure 2). Additionally, the same procedure was utilised to fabricate polymer composites reinforced with 40 wt. % PALF and 10 and 15 wt. % B_4C fillers. Following a curing period of 6 hours, the composite plate seen in Figure 3 (300 mm x 300 mm x 3 mm) was



Figure 2. Mould used for the preparation of epoxy with PALF composites.



Figure 3. Epoxy with PALF reinforced polymer composite.

fabricated. The composite plates were subsequently subjected to heat treatment for 2 hours at 75 degrees Celsius in an electric oven to facilitate drying. The 3 mm thick composite plate was precisely cut to the designated dimensions in accordance with ASTM standards for the execution of hardness, tensile, and flexural tests[37,38].

Machining these produced composites to ASTM D638 specifications allowed researchers to evaluate their mechanical properties. Tensile tests were performed on composites of 165 mm x 19 mm x 3 mm, consisting of epoxy L-12 reinforced with B4C fillers and pineapple leaf fibres[19]. The tensile properties, including tensile strength and elongation, were assessed through experimentation. The mean of three samples was recorded for each blend. The flexural characteristics of epoxy composites were analysed regarding the inclusion of PALF, in accordance



Figure 4. Tensile test specimen.



Figure 5. Flexural test specimen.

with ASTM D790 (Figure 5). Flexural tests were performed on composites of 127 mm x 12.7 mm x 3 mm, consisting of epoxy L-12 reinforced with fillers and fibres. Three samples of each composition were analysed, and the average value was reported

3.0 Results and Discussion

3.1 Tensile Properties

Figure 6 and Table 3 illustrate the results of room-temperature tensile tests conducted on epoxy L-12 composites with varying amounts of boron carbide fillers and a constant 40 wt. % of pineapple leaf fibres. Figure 6 demonstrates that the addition of fillers to the L-12 epoxy improves the average Ultimate Tensile Strength (UTS) values. Epoxy L-12 exhibits an Ultimate Tensile Strength (UTS) of 47.10 MPa. The Ultimate Tensile Strength (UTS) of epoxy L-12 with 5 wt. % B_4C and 40 wt. % PALF is 102.46 MPa, with 10 wt. % B_4C and 40 wt. % PAL is 116.56 MPa, and with 15 wt. % B_4C and 40 wt. % PAL is 123.21 MPa, respectively.

The tensile strength of epoxy L-12 composites reinforced with 15 wt. % B_4C fillers and 40 wt. % PALF was much greater than that of epoxy L-12 alone. The strength significantly increases when the system combination achieves proper contact with the supporting parts. The increased stiffness is due to the fillers and fibres, which facilitate system integration along this path. The strong interfacial bonding between the fillers, fibers and matrix helps in enhancing the properties[39,40]. The difference in production coefficients between elastic networks and fibres may have caused significant ongoing compressive

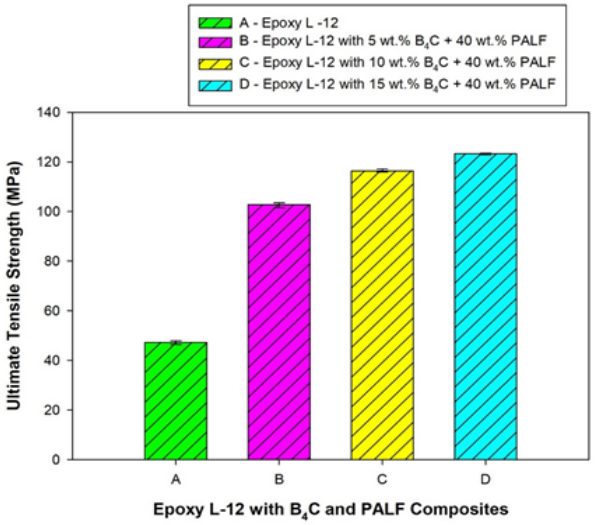


Figure 6. Ultimate strength of L-12 with boron carbide fillers and PAL fibers reinforced composites.

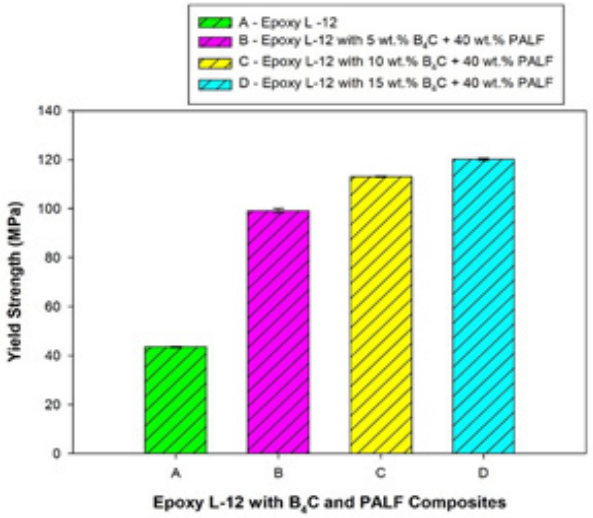


Figure 7. Yield strength of Lapox L-12 with B4C and PALF composites.

Table 3. Ultimate tensile strength of epoxy L-12 with B_4C and PALF composites

Code	Weight % of Epoxy L-12	Weight % of PALF	Weight % of B_4C Fillers	Ultimate Tensile Strength (MPa) with Standard Deviation
A	100	--	--	47.10 ± 0.75
B	55	40	5	102.46 ± 1.00
C	50	40	10	116.56 ± 0.61
D	45	40	15	123.21 ± 0.34

Table 4. Yield strength of epoxy L-12 with B_4C and PALF composites

Code	Weight % of Epoxy L-12	Weight % of PALF	Weight % of B_4C Fillers	Yield Strength (MPa) with Standard Deviation
A	100	--	--	43.50 ± 0.26
B	55	40	5	99.19 ± 0.87
C	50	40	10	113.06 ± 0.21
D	45	40	15	120.08 ± 0.44

pain linked to solidification from the expansion of these fibres[41,42].

Table 4 shows the comparison between yield strength of epoxy L-12 and epoxy L-12 with 40 wt. % of chopped pineapple fibers and 5, 10 and 15 wt. % of varying boron carbide fillers reinforced composites.

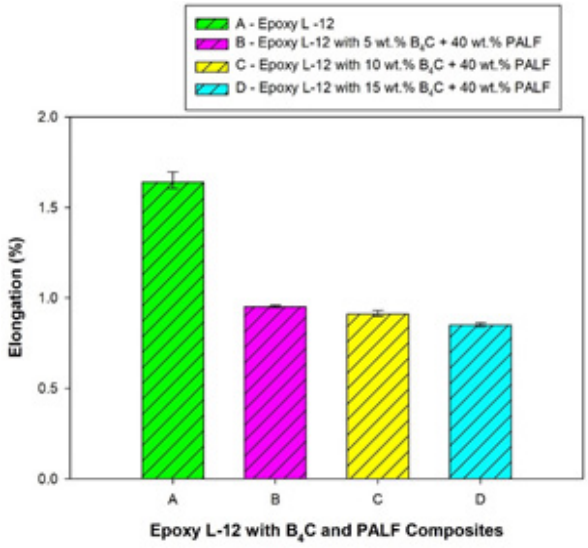


Figure 8. Elongation of epoxy with B4C and PALF reinforced composites.

Figure 7 demonstrates that the integration of fillers and fibres into L-12 epoxy improves the average yield values. Epoxy L-12 exhibits a yield strength of 43.50 MPa. The Yield Strengths (YS) of epoxy L-12 with a constant 40 wt. % of PALF and changing B_4C filler composites at 5, 10, and 15 wt. % are 99.19 MPa, 113.06 MPa, and 120.08 MPa, respectively. Figure 7 demonstrates that, relative to epoxy without fibres, the tensile values for the fiber-reinforced composite are nearly doubled, suggesting that the fibres do not diminish the composite's tensile strength. Figure 6 demonstrates the tensile strength of an L-12 epoxy reinforced with PALF composite, revealing an increase in tensile strength as filler content rises from 5 wt. % to 15 wt. %. The tensile strength of a composite material can be improved by increasing the fibre weight fraction[43,44]. Multiple investigations revealed that a composite containing 40 wt. % pineapple leaf fibres and 15 wt. % fillers had exceptional tensile strength.

Figure 8 and Table 5 illustrate the % elongation of B_4C and PALF composites. The ductility of L-12 epoxy is 1.65%, while epoxy containing 40% PALF and 5 wt. % of B_4C fillers exhibits a ductility of 0.95 %, epoxy with 40 % PALF and 10 % B_4C shows a ductility of 0.91 % and with 40 % PALF+15 % B_4C shows 0.85 %. The addition of PALF and fillers to epoxy composites diminished

Table 5. Percentage elongation of epoxy L-12 with B_4C and PALF composites

Code	Weight % of Epoxy L-12	Weight % of PALF	Weight % of B_4C Fillers	Elongation (%) with Standard Deviation
A	100	--	--	1.65 ± 0.05
B	55	40	5	0.95 ± 0.01
C	50	40	10	0.91 ± 0.02
D	45	40	15	0.85 ± 0.01

their ductility. Additionally, as illustrated in plot 7, the elongation diminishes as the 405 of PAL fibres and B_4C fillers percentage increases from 5% to 15%.

3.2 Flexural Strength

Table 6 shows the comparison between the flexural strength of epoxy L-12 and epoxy L-12 with 40% of PALF and varying wt. % of B_4C fillers reinforced composite.

Figure 9 demonstrates that the mean flexural strength values rise with the addition of fibres and carbide fillers in the L-12 epoxy. The flexural strength of epoxy L-12 is 146.37 MPa. The flexural strengths of epoxy L-12 with 5, 10, and 15 wt. % fillers and 40 wt. % PALF composites are 214.10 MPa, 230.35 MPa, and 223.83 MPa, respectively. Figure 9 demonstrates that when the weight percentage of fillers increases from 5% to 10%, the flexural strength of epoxy rises, with a minor reduction observed at 15 wt. % of carbide fillers. The increase in strength mostly arises from the integration of chopped fibres and fillers in the L-12 epoxy, which acts as a deterrent to deformation under load[45,46].

3.3 Hardness

Table 7 shows the comparison between the hardness of epoxy L-12 and epoxy with fillers and PALF reinforced composites.

Figure 10 illustrates that the mean hardness values rise with the addition of fibres and fillers in the L-12 epoxy. The hardness of epoxy L-12 is quantified at 46.10. The hardness of epoxy L-12 reinforced composites with 40 wt. % of PALF and 5, 10, and 15 wt. % of B_4C filler is 83.90, 88.15, and 95.25, respectively. Figure 10 demonstrates

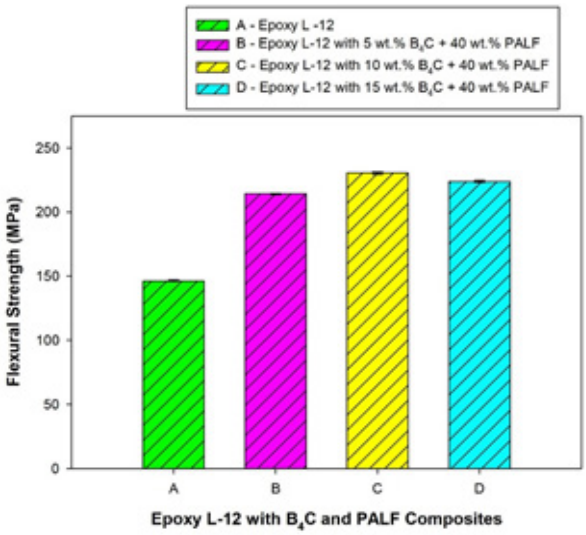


Figure 9. Flexural strength of B4C fillers and PAL fibers composites.

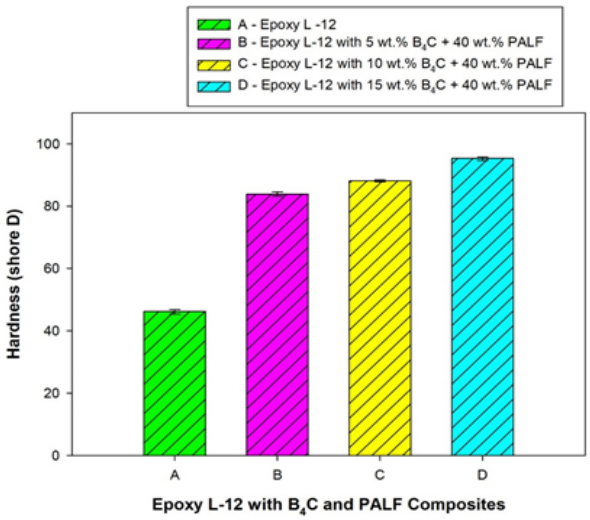


Figure 10. Hardness of epoxy L-12 with B4C fillers and PALF composites.

Table 6. Flexural strength of Lapox L-12 with B_4C and PALF composites

Code	Weight % of Epoxy L-12	Weight % of PALF	Weight % of B_4C Fillers	Flexural Strength (MPa) with Standard Deviation
A	100	--	--	146.37 ± 0.80
B	55	40	5	214.10 ± 0.52
C	50	40	10	230.35 ± 0.94
D	45	40	15	223.83 ± 0.95

Table 7. Hardness of epoxy L-12 with B_4C fillers and PALF composites

Code	Weight % of Epoxy L-12	Weight % of PALF	Weight % of B_4C Fillers	Hardness (Shore D) with Standard Deviation
A	100	--	--	46.10 ± 0.75
B	55	40	5	83.90 ± 0.65
C	50	40	10	88.15 ± 0.28
D	45	40	15	95.25 ± 0.55

that an increase in the weight percentage of B_4C fillers and PAL fibres corresponds with a rise in the hardness of the epoxy. The increase in hardness is mainly due to the addition of fillers and chopped fibres in the L-12 epoxy, which acts as a barrier to deformation under stress.

4.0 Conclusions

This experiment investigated the mechanical properties of L-12 epoxy composites reinforced with different weight percentages of B_4C fillers and a constant weight percentage of pineapple leaf fibre. L-12 epoxy composites incorporating 5, 10, and 15 wt. % of B_4C fillers, together with a constant 40 wt. % of PALF, were effectively produced via the hand layup technique and cured at 75˚C for a duration of 2 hours. There is a significant improvement in tensile characteristics when comparing epoxy reinforced with fibre to epoxy without reinforcement. The investigation's results demonstrate an improvement in the tensile strength of the fibre material composite. Epoxy composites containing 5, 10, and 15 wt. % of B_4C fillers and pineapple leaf fibres exhibited improved ultimate and yield strength. Epoxy L-12 using 15 wt. % B_4C fillers and 40 wt. % PAL fibres exhibited increases of 61.7 % in ultimate strength and 63.7 % in yield strength, respectively. The elongation of fillers and PALF epoxy composites decreased as the filler weight percentage increased from 5 to 15 wt. %. Epoxy incorporating 15 wt. % B_4C filler and 40 wt. % PALF composites demonstrates improved flexural strength and hardness.

5.0 References

1. Maharramov AM, Ramazanov MA, Ahmadova AB, Hajiyeva FV, Hasanova UA. Thermal and mechanical properties of polymer-based nanocomposites of isotactic polypropylene and titanium nanoparticles. Digest J Nanomater Biostruct. 2016; 11(2):365-72.
2. Lee GW, Park M, Kim J, Lee JI, Yoon HG. Enhanced thermal conductivity of polymer composites filled with hybrid filler. Composites Part A. 2006; 37:727-34. https://doi.org/10.1016/j.compositesa.2005.07.006
3. Ali Z, Muthuraman V, Rathnakumar P, Gurusamy P, Nagaral M. Studies on mechanical properties of 3 wt % of 40 and 90 µm size B4C particulates reinforced A356 alloy composites. Mater Today Proc. 2022; 52:494-9. https://doi.org/10.1016/j.matpr.2021.09.260
4. Nagaraj N, Mahendra KV, Nagaral M. Microstructure and evaluation of mechanical properties of Al-7Si-fly ash composites. Mater Today Proc. 2018; 5(1):3109-16. https://doi.org/10.1016/j.matpr.2018.01.116
5. Ali Z, Muthuraman V, Rathnakumar P, Gurusamy P, Nagaral M. Investigation on the tribological properties of copper alloy reinforced with Gr/ZrO_2 particulates by stir casting route. Mater Today Proc. 2020; 33:3449-53. https://doi.org/10.1016/j.matpr.2020.05.351
6. Hanumantharayappa AKB, Prasanna C, Ragavendra CC, Beekam CS, Boluvar LS, Nagaral M, *et al*. Synthesis and mechanical characterization of Si_3N_4 reinforced copper-tin matrix composites. J Mech Behav Mater. 2021; 30(1):199-206. https://doi.org/10.1515/jmbm-2021-0020
7. Dama K, Prashanth L, Nagaral M, Mathapati R, Hanumantharayagouda MB. Microstructure and mechanical behavior of B4C particulates reinforced ZA27 alloy composites. Mater Today Proc. 2017; 4(8):7546-53. https://doi.org/10.1016/j.matpr.2017.07.086
8. Rahman MR, Hasan M, Huque MM, Islam MN. Physico-mechanical properties of jute fiber reinforced polypropylene composites. J Reinf Plast Compos. 2010; 29(3):445-55. https://doi.org/10.1177/0731684408098008
9. Venkataraman V, Nagaral M. Mechanical characterization and wear behavior of aerospace alloy AA2124 and micro

B4C reinforced metal composites. J Met Mater Miner. 2020; 30(4):97-105. https://doi.org/10.55713/jmmm.v30i4.641

10. Manjunatha TH, Basavaraj Y, Nagaral M, Venkataramana V, Harti JI. Investigations on mechanical behavior of Al7075-nano B4C composites. IOP Conf Ser Mater Sci Eng. 2018; 376:012091. https://doi.org/10.1088/1757-899X/376/1/012091
11. Kumar HSV, Kempaiah UN, Nagaral M, Auradi V. Impact, tensile and fatigue failure analysis of boron carbide particles reinforced Al-Mg-Si (Al6061) alloy composites. J Fail Anal Prev. 2021; 21(6):2177-89. https://doi.org/10.1007/s11668-021-01265-w
12. Jadhav PR, Nagaral M, Rachoti S, Harti JI. Impact of boron carbide and graphite dual particulates addition on wear behavior of A356 alloy metal matrix composites. J Met Mater Miner. 2020; 30(4):106-12. https://doi.org/10.55713/jmmm.v30i4.642
13. Adaveesh B, Prabhushankar GV, Nagaral M. Tribological and tensile behaviour of Si3N4 reinforced Cu-Sn matrix composites. Mater Phys Mech. 2023; 51(4):11-22.
14. Yadav PS, Purohit R, Kothari A. The effect of nano SiO_2 on the mechanical and tribological properties of hybrid polymer matrix composites: a review. Adv Mater Manuf Charact. 2017; 7(2):101-10. https://doi.org/10.11127/ijammc2017.10.12
15. Jani SP, Kumar AS, Khan MA, Sajith S, Saravanan A. Influence of natural filler on mechanical properties of hemp/kevlar hybrid green composite and analysis of change in material behavior using acoustic emission. J Nat Fibers. 2021; 18(11):1580-91. https://doi.org/10.1080/15440478.2019.1692321
16. Bharath V, Auradi V, Kumar GBV, Nagaral M, Chavali M, Helal M, *et al*. Microstructural evolution, tensile failure, fatigue behavior and wear properties of Al2O3 reinforced Al2014 alloy T6 heat treated metal composites. Materials. 2022; 15(12):4244. https://doi.org/10.3390/ma15124244
17. Priyankar D, Ali Z, Nagaral M, Rathnakumar P, Muthuraman V, Umar MD. Microstructure and evolution of mechanical properties of Cu-Sn alloy with graphite and nano zirconium oxide particulates. Mater Today Proc. 2022; 52:296-300. https://doi.org/10.1016/j.matpr.2021.08.300
18. Shetty RP, Mahesh TS, Ali Z, Veeresha G, Nagaral M. Studies on mechanical behaviour and tensile fractography of boron carbide particles reinforced Al8081 alloy advanced metal composites. Mater Today Proc. 2022; 52:2115-20. https://doi.org/10.1016/j.matpr.2021.12.397
19. Chandrasekhar GL, Vijayakumar Y, Nagaral M, Anilkumar C. Microstructural evaluation and mechanical behaviour of nano B4C reinforced Al7475 alloy metal composites. Int J Veh Struct Syst. 2021; 13(5). https://doi.org/10.4273/ijvss.13.5.24
20. Nagaraj N, Mahendra KV, Nagaral M. Investigations on mechanical behaviour of micro graphite particulates reinforced Al-7Si alloy composites. IOP Conf Ser Mater Sci Eng. 2018; 310:012111. https://doi.org/10.1088/1757-899X/310/1/012131
21. Markandan K, Lai CQ. Fabrication, properties and applications of polymer composites additively manufactured with filler alignment control: A review. Composites Part B Eng. 2023; 256:110661. https://doi.org/10.1016/j.compositesb.2023.110661
22. Sivaram RN, Thiagamani SMK, Sivakumar P, Srinivasan M, Yagna SNB, Hossein EK, *et al*. Isolation and characterization of agro waste biomass sapodilla seeds as reinforcement in potential polymer composite applications. Heliyon. 2023; 9(7):e17760. https://doi.org/10.1016/j.heliyon.2023.e17760
23. Kumar HSV, Revanna K, Kumar N, Sathyanarayana N, Nagaral M, Manjunath GA, *et al*. Impact of silicon carbide particles weight percentage on the microstructure, mechanical behaviour, and fractography of Al2014 alloy composites. Adv Mater Sci Eng. 2022. https://doi.org/10.1155/2022/2839150
24. Somayaji A, Nagaral M, Anjinappa C, Alkahtani MQ, Billady RK, Kumar N, *et al*. Influence of graphite particles on the mechanical and wear characterization of Al6082 alloy composites. ACS Omega. 2023; 8(30):26828-36. https://doi.org/10.1021/acsomega.3c01313
25. Raksha MS, Nagaral M, Boppana SB, Anjinappa C, Khan MS, Wahab MOA, *et al*. Impact of boron carbide particles and weight percentage on the mechanical and wear characterization of Al2011 alloy metal composites. ACS Omega. 2023; 8(26):23763-71. https://doi.org/10.1021/acsomega.3c02065
26. Shetty RP, Raju TH, Nagaral M, Kumar N, Auradi V. Effect of B4C particles addition on the mechanical, tensile fracture and wear behavior of Al7075 alloy composites. J Bio Tribo Corros. 2024; 10(2):32. https://doi.org/10.1007/s40735-024-00841-5
27. Lal LPJ, Ramesh S, Natarajan E. Study on the repeatability of manufacturing nano-silica (SiO2) reinforced composite laminates. IOP Conf Ser Mater Sci

Eng. 2018; 346:012083. https://doi.org/10.1088/1757-899X/346/1/012083
28. Drzal M, Mohanty LT, Misra AK. Bio-composite materials as alternatives to petroleum-based composites for automotive applications. Magnesium. 2001; 40:1-3.
29. Ali Z, Muthuraman V, Rathnakumar P, Gurusamy P, Nagaral M. Influence of B4C particle size on the mechanical behavior of A356 aluminium composites. Res Eng Struct Mater. 2023; 9(2):527-40.
30. Mohan RM, Kempaiah UN, Manjunatha B, Nagaral M, Auradi V. Processing and wear behavior optimization of B4C and rice husk ash dual particles reinforced ADC12 alloy composites using Taguchi method. Mater Phys Mech. 2022; 50(2).
31. Nayak PH, Srinivas HK, Rajendra P, Nagaral M, Raviprakash M, Auradi V. Effect of nano zirconium oxide (ZrO2) particles addition on the mechanical behavior and tensile fractography of copper tin (Cu-Sn) alloy nano composites. Struct Integr Life. 2022; 22(3).
32. Kambaiah R, Suresh R, Nagaral M, Auradi V, Anjinappa C, Garse K, *et al*. Mechanical-wear behavior and microstructure analysis of Al2214 alloy with B4C and graphite particles hybrid composites. Eng Rep. 2024; 12876. https://doi.org/10.1002/eng2.12876
33. Syduzzaman M, Chowdhury SE, Pritha NM, Hassan A, Hossain S. Natural fiber reinforced polymer composites for ballistic protection: Design, performance, and challenges. Results Mater. 2024; 24:100639. https://doi.org/10.1016/j.rinma.2024.100639
34. Olanrewaju O, Oladele IO, Adelani SO. Recent advances in natural fiber reinforced metal/ceramic/polymer composites: An overview of the structure property relationship for engineering applications. Hybrid Adv. 2025; 8:100378. https://doi.org/10.1016/j.hybadv.2025.100378
35. Adaveesh B, Raghukumar J, Nagaral M. Investigations on wear behaviour of micro B4C particulates reinforced Al7010 alloy composites. IOP Conf Ser Mater Sci Eng. 2018; 310:012155. https://doi.org/10.1088/1757-899X/310/1/012155
36. Madhu D, Patil S, Nagaral M, Dayanand S, Anjinappa C, Majdi A, *et al*. Synthesis and tensile characterisation of B4C particles reinforced Al7475 (Al-Zn) alloy composites. J Mines Met Fuels. 2024;251-62. https://doi.org/10.18311/jmmf/2024/43745
37. Angadi SB, Kumar S, Nagaral M, Auradi V, Valukula B. Effect of ceramic boron carbide particles addition on the mechanical and microstructural characteristics of Al7020 alloy composites. Mech Adv Compos Struct. 2025; 12(1):169-18.
38. Krishnappa A, Ramesh S, Bharath VM, Siddagangappa R, Ashokkumar S, Nagaral M, *et al*. Effect of hybrid nano particle reinforcements on fractographic, mechanical and wear behavior of Al6061 alloy composites developed by ultrasonic assisted stir casting technique. Fract Struct Integr. 2025; 19(71):285-301. https://doi.org/10.3221/IGF-ESIS.71.21
39. Shetty SK, Nayak M, Nagaral M, Auradi V, Nalband F. Influence of electroless copper coated B4C particles addition on the hardness, density and wear behavior of Al2025 alloy composites. J Bio Tribo Corros. 2024; 10(4):1-16. https://doi.org/10.1007/s40735-024-00916-3
40. Nithin BN, Nagaral M, Maiyya M, Nalband F, Auradi V. Mechanical properties of ZrO_2 particles reinforced Al2219 alloy metal composites prepared by stir casting process. J Mines Met Fuels. 2024; 37-47.
41. Ahmad N, Verma M, Nagaral M, Kachhap S. Microstructural characteristics and wear properties of Si_3N_4/ZrO_2 reinforced Al7055 alloy T6 heat treated metal matrix composites. Interactions. 2024; 245(1):310. https://doi.org/10.1007/s10751-024-02138-y
42. Ramachandra GS, Boppana SB, Dayanand S, Nagaral M, Singh AK. Wear behavior of Si_3N_4 reinforced AA2219 metal matrix composites. J Mines Met Fuels. 2024; 72(7):725-30. https://doi.org/10.18311/jmmf/2024/45062
43. Kiran MD, Govindaraju HK, Kumar N, Nagaral M, Khankal DV, Pandhare AP, *et al*. Effect of CNT filler and temperature on fracture toughness of epoxy composites reinforced with carbon fabric. Eng Rep. 2024; 6(8):e12816. https://doi.org/10.1002/eng2.12816
44. Dayanand S, Babu BS, Telagu A, Mukunda S, Singh AK, Nagaral M. A review on carbon fiber reinforced metal matrix composites. J Mines Met Fuels. 2024; 72(4):333-46. https://doi.org/10.18311/jmmf/2024/44015
45. Kumar N, Kumar HSV, Raju TH, Nagaral M, Auradi V, Veeresha RK. Microstructural characterization, mechanical and Taguchi wear behavior of micro-titanium carbide particle-reinforced Al2014 alloy composites synthesized by advanced two-stage casting method. J Bio Tribo Corros. 2022; 8(4):109. https://doi.org/10.1007/s40735-022-00709-6
46. Matti S, Shivakumar BP, Nagaral M, Shashidhar S, Siddappa PN, Auradi V. Mechanical and tribological behavior of flyash, red mud and mica particles reinforced Al7075 alloy hybrid metal composites. Manuf Rev. 2022; 9:11. https://doi.org/10.1051/mfreview/2022009