



Engineering of bamboo fiber and glass fiber composites with B₄C filler for fire-resistant structural material applications

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Abstract

The increasing demand for lightweight, high-strength, and fire-resistant materials has driven the development of hybrid epoxy composites reinforced with bamboo fibre (SB) and glass fibre (SK), incorporating boron carbide (B₄C) as a functional filler. This study investigates the effects of composition and B₄C content on the physical, mechanical, and fire-resistant properties of hybrid epoxy composites. Four formulations (100E, 70E30SB, 70E30SK, and 70E15SB15SK) were prepared with B₄C contents of 0, 2.5, and 5 wt%. The composites were evaluated for density, tensile strength, elongation, impact strength, Shore-D hardness, and fire resistance (limiting oxygen index (LOI), char yield, and burning rate). The results show that density increases with increasing B₄C content. A filler content of 2.5 wt% provides the most consistent improvement in mechanical properties, with the highest tensile strength observed in the 70E30SK composite (317 MPa). However, increasing the B₄C content to 5 wt% reduces several mechanical properties due to particle agglomeration. In the Shore-D hardness test, an increase is observed in 70E30SB, while 70E30SK and 70E15SB15SK decrease at 2.5 wt% B₄C before increasing again at 5 wt%. In impact testing, 70E30SK shows the highest toughness without B₄C, whereas 70E30SB and 70E15SB15SK improve at 5 wt% B₄C. In terms of flammability, B₄C increases the LOI and reduces the burning rate, particularly in glass fibre-rich composites, although changes in char yield are not always significant. Overall, B₄C improves fire resistance and can enhance mechanical performance when dispersed under optimal conditions.

Keywords:

Hybrid composite, bamboo fibre, glass fibre, boron carbide (B₄C), fire resistance.

1 Introduction

The use of composite materials continues to grow rapidly, in line with the need for lightweight, strong, and multifunctional materials. In 2024, global composite material use will have increased by 45.3% since 2019, with continued growth projected in the following years [1]. This data shows that composites are strategic engineering materials for the development of various sectors, including the automotive, construction, and defence industries [2]. However, not all types of composites can meet increasingly high performance demands. In particular, challenges remain in producing lightweight materials with high mechanical strength and good fire resistance for modern applications.

To address the challenges of modern applications, the use of natural fibres as composite reinforcements has gained widespread

attention due to their lightweight properties, abundant availability, and potential to enhance composite strength. One promising natural fibre is bamboo fibre, which offers the advantages of low density, easy availability, and contributes to composite strength[3], [4]. The literature reports a range of bamboo fibre density values of 0.46-1.12 g/cm³[5]. In addition, the use of bamboo fibres in epoxy resin can increase tensile strength up to 33.5 MPa [6]. However, these mechanical strength values remain a constraint for natural fibres, as they are far lower than those of synthetic fibres. This constraint has prompted the need for additional reinforcement strategies, such as combining synthetic fibres or adding fillers.

Research by Yudha [7] shows that the addition of glass fibre can increase tensile strength by up to 58% with a SK, SB, SB, SK (glass fibre, bamboo fibre, bamboo fibre, glass fibre) composition. However, combining these two fibres still faces obstacles. The adhesion challenge in bamboo-glass hybrids stems from the polarity mismatch between highly hydrophilic bamboo fibres and a polymer matrix that tends to be more hydrophobic [8], [9]. This can lead to weak interfacial bonds, the formation of voids, and an increased risk of delamination [10]. In addition, modern composite applications must also have good fire resistance to compete with metal materials. Recent data shows that glass fibre composites have an LOI (Limiting Oxygen Index) value in the range of 21-34.5% [11]. With this value, the current fire resistance performance remains inadequate for high-risk applications; it is necessary to add B₄C as a condensation barrier to raise the LOI. Based on this, there is a need for the development of materials that can improve physical properties and enhance the reliability of composite structures.

One approach extensively researched to improve the reliability of a material is the addition of nanomaterials or inorganic fillers. Among the various candidates, boron carbide (B₄C) is a potential choice because it has a relatively low density for ceramics (2.5 g/cm³), very high hardness, and good thermal stability [12]. The addition of B₄C is intended to fill the gaps and pores between the matrix and fibres, thereby increasing density and reducing void formation. In terms of thermal resistance, B₄C can oxidise at high temperatures to form a B₂O₃ layer that acts as a heat and oxygen diffusion barrier, thereby suppressing volatile diffusion and potentially increasing LOI. This improvement in fire resistance is closely associated with the formation of this protective oxide layer at elevated temperatures. According to data, B₄C begins to oxidize at 600 °C and remains thermally stable up to 1600 °C, indicating that B₄C can suppress O₂/volatile diffusion, thereby potentially increasing the LOI of the composite [13].

On the other hand, the high intrinsic hardness of B₄C contributes to increased surface resistance and stiffness of the composite. The addition of 4 wt% nano-B₄C has been reported to achieve a Shore D hardness of 73 [14], making it more resistant to wear and deformation. Thus, the use of B₄C as a filler not only addresses the limitations of bamboo fibre-glass fibre hybridisation but also enhances both mechanical performance and fire resistance.

Although many studies have evaluated the characteristics of fibre-based composites, most still focus on single systems, whether based on natural fibres (e.g., bamboo, hemp, or kenaf) or synthetic fibres such as glass fibres [2], [15]. However, each type of fibre has inherent limitations; bamboo fibre-based composites tend to exhibit relatively low mechanical strength, while glass fibre-based composites, despite their superior strength, remain prone to interfacial adhesion issues and delamination [7], [16]. To address these limitations, the incorporation of inorganic fillers such as boron carbide (B₄C) has been proposed to enhance composite performance, particularly in terms of fire resistance and hardness. Nevertheless, to the best of the authors' knowledge, studies investigating the combined effects of bamboo-glass fibre hybridisation and B₄C filler on both mechanical properties and fire resistance of epoxy composites remain limited. Based on this gap, this study aims to develop and characterise epoxy-based composites reinforced with bamboo and glass fibres at varying B₄C contents to obtain lightweight materials with improved mechanical performance and fire resistance.

The development of hybrid composites based on bamboo and glass fibres, with the addition of boron carbide (B₄C) filler, has great potential to meet modern engineering material needs, not only by using renewable resources such as bamboo fibres but also by improving mechanical performance and fire resistance for strategic applications. This approach not only overcomes the limitations of natural fibres, which tend to be flammable and have low strength, but also optimises the advantages of glass fibres and utilises the unique properties of B₄C, which is hard and heat-resistant. This research not only offers technical solutions to the challenges of designing composites that are lightweight, strong, and fire-resistant, but also makes a strategic contribution to the development of multifunctional materials that can be applied in the transportation, construction, and defense sectors, in line with the demands for sustainable and highly competitive material innovation.

2 Research methodology

2.1 Material

The bamboo fibre (SB) used in this study is of the *Neololeba atra* species, with a density of 0.78 g/cm³ and a thickness of 1 mm as measured with a vernier calliper, obtained from bamboo trees in the Malang area, East Java. Glass fibre (SK) with 600 GSM and a density of 2.6 g/cm³. Boron carbide (B₄C) with a density of 2.52 g/cm³ and a size of 25 μm. Eposchon brand bisphenol A-epichlorohydrin epoxy resin with a density of 1.159 g/cm³ and Eposchon brand polyaminoamide catalyst with a density of 1.04 g/cm³.

2.2 Bamboo fibre preparation

In this study, bamboo fibre was used as a composite reinforcement sourced from bamboo trees. First, the bamboo trees were cut into small pieces measuring 5 x 250 mm with a thickness of 1 mm. Then, the bamboo pieces were treated with 6% NaOH for 24 hours at room temperature. The alkalisied bamboo pieces were neutralised with deionised water until pH 7. After this procedure, the bamboo pieces were dried for 24 hours. The dried bamboo pieces were woven into 250 x 250 mm squares.

2.3 Composite fabrication

This study used woven bamboo fibre and glass fibre as reinforcements, boron carbide as filler, and epoxy resin as matrix for composite fabrication. Composites were fabricated at room temperature using the hand-lay-up method under pressure. The Design of Experiment used in this study is shown in Table 1.

Table 1. Design of experiment

Sample	Bamboo Fibre (v/v)	Glass Fibre(v/v)	Epoxy Resin (v/v)	B ₄ C (wt%)
100E	0	0	100	0
	0	0	100	2,5
	0	0	100	5
70E30SB	30	0	70	0
	30	0	70	2,5
	30	0	70	5
70E30SK	0	20	70	0
	0	30	70	2,5
	0	30	70	5
70E15SB15SK	15	15	70	0
	15	15	70	2,5
	15	15	70	5

The masses were first calculated based on the composite's total volume, taking into account the composite's constituent densities. Meanwhile, the mass of B₄C is determined from the mass of epoxy resin. The second step was to heat the epoxy resin to 75°C for 2 minutes to reduce its viscosity. After reaching the desired temperature, B₄C particles were gradually added into the epoxy resin and mixed using a magnetic stirrer at 200 rpm for 3 minutes. B₄C was gradually added and continuously stirred to promote uniform

dispersion and minimise particle agglomeration. The catalyst is added in the next step at a mass ratio of 2:1 and stirred at 250 rpm for 3 minutes. After the three are mixed until homogeneous, some of the resin is poured onto a wax-coated glass base, followed by the placement of glass fibres. After that, some of the resin was poured over the glass fibres again, followed by the placement of bamboo fibre weaving. This was repeated for 3 layers (SK, SB, SK). To remove trapped air bubbles, the excess resin was rolled evenly and loaded at 25 kg. The composite is dried for 24 hours at room temperature. Once dry, the composite undergoes a two-stage post-curing process, with the first stage at 75°C for 2 hours, followed by a second stage at 135°C for 3 hours. Fig. 1 shows the flow chart of the composite fabrication process.

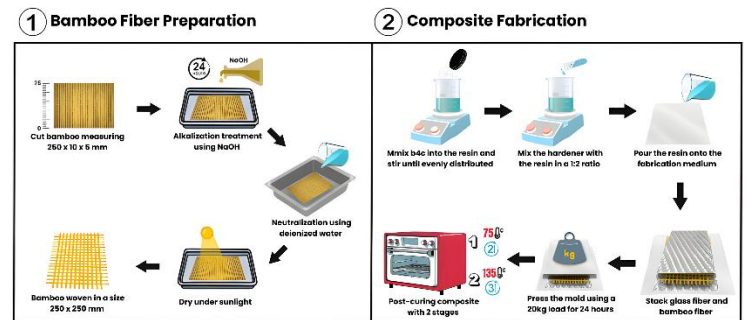


Fig. 1. Composite fabrication process

2.4 Characterization

2.4.1 Density test

The density of each sample was determined by measuring its mass using an analytical balance and its volume using a digital caliper. The measurements were expressed in g/cm³. To improve accuracy, each sample was measured three times, and the average value was reported. The density value was calculated using Eq. (1) below.

$$\text{Density, } (\rho) = \frac{\text{mass}}{\text{volume}} \left(\frac{\text{g}}{\text{cm}^3} \right) \quad (1)$$

2.4.2 Tensile test

The composite was subjected to tensile testing to determine its mechanical properties. The tensile test was conducted using a Universal Testing Machine (UTM) in accordance with ASTM D368. The tensile strength and percentage elongation were calculated using Eq. (2) and (3).

$$\text{Tensile Strength, } \sigma \text{ (MPa)} = \frac{F}{A} \quad (2)$$

$$\text{Elongation, } \varepsilon \text{ (\%)} = \frac{P_1 - P_0}{P_0} \times 100\% \quad (3)$$

2.4.3 Impact test

Impact testing is conducted to determine the material's ability to absorb impact energy, thereby assessing its toughness and resistance to dynamic loads. The testing refers to the Charpy impact test, as specified in ASTM D6110. Impact energy and impact strength are calculated sequentially using Eqs. (4) and (5).

$$\text{Impact Energy} = m \cdot g \cdot l (\cos \beta - \cos \alpha) \quad (4)$$

$$\text{Impact Strength} = \frac{\Delta E}{A} \quad (5)$$

2.4.4 Hardness test

Hardness testing is conducted to determine the hardness and toughness of composite surfaces. Testing is performed using a Shore-D Durometer Hardness Tester in accordance with ASTM D2240 standards. Hardness values are read directly from the durometer scale at the time of indentation during testing.

2.4.5 Flammability test

Flammability testing was conducted vertically in accordance with ASTM D3014, which is more accurate than horizontal testing. The parameters measured in this test included burning time, char yield (CY), and limiting oxygen index (LOI) of each composite, which were calculated using Equations (6-8).

$$v = L \times \frac{60}{t} \quad (6)$$

$$CY = \frac{w_1}{w_0} \quad (7)$$

$$LOI = 17,5 + 0,4 \times CY \quad (8)$$

L is the distance between two marks used to measure the spread of fire, with a value of L = 75 mm, while t is the time (in minutes) required for the fire to spread. w_0 indicates the initial mass of the sample (g), and w_1 is the residual mass of the composite sample after combustion (g). Before testing, the composite sample is stored for 48 hours in a temperature-controlled room (25°C) using a thermostat. The test begins by drawing a line of 25-100 mm from the end of the sample. After that, a 25 mm high Bunsen flame is directed at the edge of the sample. The Bunsen flame is extinguished if, within 30 seconds, the flame reaches the 25 mm mark. The time required for the flame to spread from the 25 to 100 mm mark is then recorded to determine the burning rate.

3 Result and discussion

3.1 Density

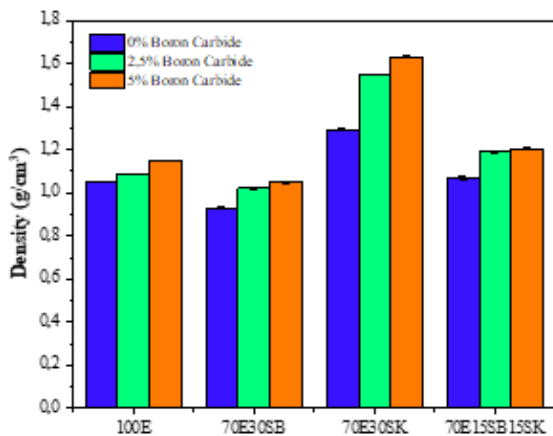


Fig. 2. Density

The density values of the composites are shown in Figure 2. The graph shows an increasing trend in density values as the fraction of boron carbide increases. In pure epoxy composites (100E), the density increased from $1.051 \pm 0.0035 \text{ g/cm}^3$ at 0% boron carbide to $1.149 \pm 0.00284 \text{ g/cm}^3$ at 5% boron carbide. The bamboo fibre-based composite (70E30SB) had the lowest density, namely $0.930 \pm 0.00416 \text{ g/cm}^3$ (0%), which increased to $1.051 \pm 0.00439 \text{ g/cm}^3$ (5%), while the glass fibre-based composite (70E30SK) showed a significant increase from $1.295 \pm 0.00309 \text{ g/cm}^3$ (0%) to $1.632 \pm 0.00327 \text{ g/cm}^3$ (5%). Meanwhile, the hybrid composite (70E15SB15SK) showed an intermediate increase in density, from $1.071 \pm 0.00667 \text{ g/cm}^3$ (0%) to $1.204 \pm 0.00476 \text{ g/cm}^3$ (5%). The increase in density is not only attributed to the higher intrinsic density of B₄C (2.5 g/cm³), but also to microstructural changes

within the composite. The addition of B₄C particles improves packing efficiency by occupying void spaces between the matrix and reinforcing fibres, thereby reducing porosity and increasing the overall compactness of the material. This is consistent with previous findings by Harigovindan [17], which indicate that B₄C can fill micro-voids and enhance interfacial contact, thereby increasing density.

Based on Figure 2, the type of fibre also affects the density of the composite. At all B₄C concentrations, the density order is consistent: glass fibre (70E30SK) has the highest density, hybrid (70E15SB15SK) has a medium density, and bamboo fibre (70E30SB) has the lowest density. For example, in the absence of B₄C (0%), 70E30SK showed the highest density ($1.295 \pm 0.003 \text{ g/cm}^3$), followed by 70E15SB15SK ($1.071 \pm 0.007 \text{ g/cm}^3$), while 70E30SB had the lowest density ($0.930 \pm 0.004 \text{ g/cm}^3$). This trend can be explained not only by the rule of mixtures but also by differences in fibre characteristics. Glass fibres have a higher intrinsic density (2.6 g/cm³), a more uniform geometry, and lower porosity, resulting in better packing and fewer voids within the composite. In contrast, bamboo fibres have lower density (0.78 g/cm³), higher porosity, and heterogeneous morphology, which tend to introduce more voids and reduce packing efficiency. Consequently, composites reinforced with glass fibres exhibit higher density, while bamboo fibre composites show lower density [18]. In hybrid composites, the combination of bamboo and glass fibres results in intermediate density due to the competing effects of high-density glass fibres and low-density bamboo fibres, as well as variations in fibre distribution and packing arrangement within the matrix.

3.2 Tensile strength

The tensile test results shown in Fig. 3 indicate that the addition of B₄C filler plays a dominant role in the mechanical response of the composite. Based on the B₄C filler fraction, the lowest tensile strength and elongation values occur at a composition of 0% B₄C, which then increases significantly at 2.5% B₄C and decreases at 5% B₄C. The addition of 2.5% B₄C across all compositions resulted in consistent increases in tensile strength and elongation.

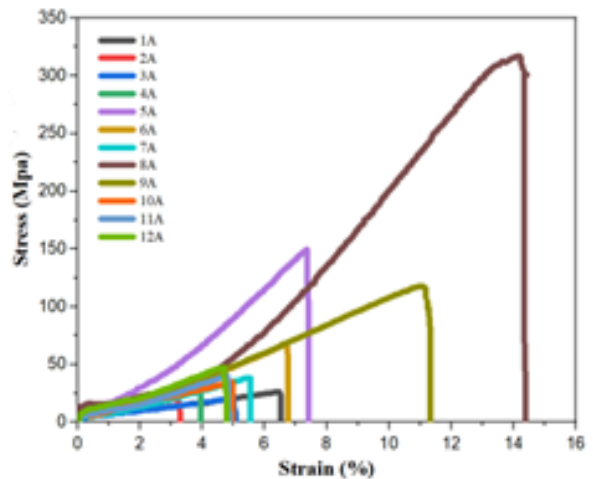


Fig. 3. Graph of Stress and Strain

The most notable increase occurred in 70E30SK, with 112% increases in tensile strength and 92% in elongation compared to the condition without B₄C. The hybrid composite also increased tensile strength by 75% and elongation by 65%, followed by 70E30SB and 100E. Conversely, at 5% B₄C, there was a decrease in tensile strength and elongation in all reinforcement fibre variations. The most drastic decrease was observed in 70E30SK, which fell by 87%. This trend indicates that at low concentrations, B₄C particles are well dispersed, enabling them to act as micro-reinforcements that facilitate load transfer to the fibres and increase the composite's tensile strength [19]. However, at a higher filler content (5% B₄C),

particle agglomeration becomes more pronounced, leading to the formation of micro-voids and non-uniform stress distribution within the composite. These agglomerated regions act as stress-concentration sites, significantly reducing load-transfer efficiency and promoting premature crack initiation [20]. As a result, the mechanical response of the composite shifts from a relatively ductile behaviour at lower filler content to a more brittle behaviour at higher filler content. This is characterised by reduced elongation at break, limited plastic deformation, and rapid crack propagation once failure is initiated.

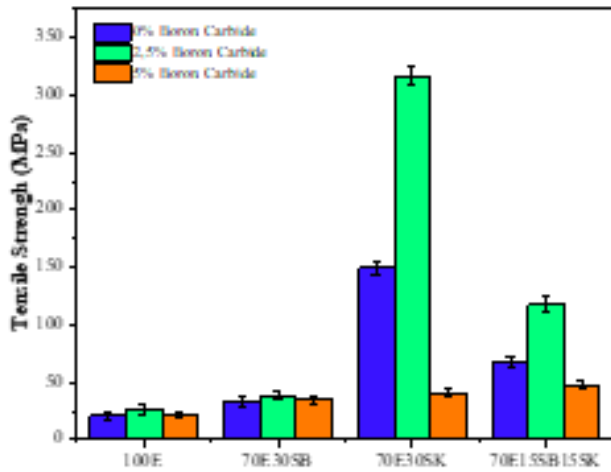


Fig. 4. Tensile Strength

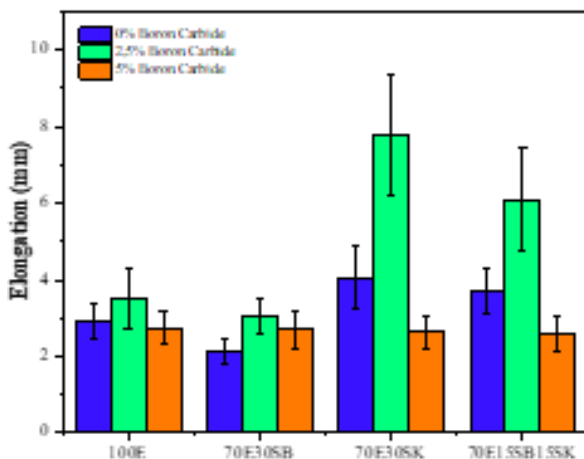


Fig. 5. Elongation

In addition to the influence of the B₄C fraction, differences in the reinforcing fibres also affect the mechanical response of the composite. This is evidenced by the lowest tensile strength and elongation values of pure epoxy without fibres (100E). The tensile strength and elongation values then increase when fibres are added. The addition of bamboo fibres (70E30SB) increased the tensile strength to 33.20 ± 4.14 MPa (elongation 2.12 ± 0.35 mm), while glass fibres (70E30SK) provided the greatest leap with a tensile strength value of 149.4 ± 6.17 MPa with elongation of 4.06 ± 0.80 mm. Meanwhile, the hybrid composite (70E15SB15SK) had intermediate values with a tensile strength of 67.4 ± 5.43 MPa and elongation of 3.70 ± 0.59 mm. Glass fibres provided the largest increase in value due to their uniform diameter and sized interface, which increased the IFSS value and facilitated load transfer [21]. Bamboo fibres have the lowest value compared to other types of reinforcing fibres due to the heterogeneous lignocellulose morphology of bamboo fibres and the hygroscopic properties of bamboo fibres, which weaken the bond between the fibres and the matrix [7], [22]. Meanwhile, hybrid fibres have a medium value because they receive strength contributions from glass fibres, which are still limited by bamboo fibres' properties.

3.3 Impact strength

Based on the results of the carpy impact test in Fig. 6, the addition of B₄C shows a composition-specific effect on the impact strength value. Based on the data, 70E30S has the highest impact value under conditions without B₄C (0.0423 ± 0.0084 J/mm²) but shows a sharp decline when 2.5% B₄C is added (0.0201 ± 0.0025 J/mm²) and only partially recovers at 5% (0.0295 ± 0.0021 J/mm²). Conversely, 70E30SB increased from 0.0139 ± 0.0033 J/mm² (0% B₄C) to 0.0271 ± 0.0037 J/mm² (5% B₄C), and the 70E15SB15SK hybrid showed a gradual increase to 0.0379 ± 0.0051 J/mm² at 5% B₄C. This pattern indicates two opposing mechanisms: with good B₄C particle dispersion, these hard particles can function as micro-reinforcements (crack-deflection, particle-bridging, and energy absorption), thereby increasing the ability to absorb impact energy; but under poor dispersion/agglomeration conditions, B₄C particles become stress concentrators and crack initiation zones that actually reduce impact (a typical decrease is seen in 70E30SK at 2.5% B₄C). These experimental findings are consistent with reports that B₄C improves mechanical properties when homogeneously dispersed, but agglomeration and increased local porosity reduce impact performance [23], [24].

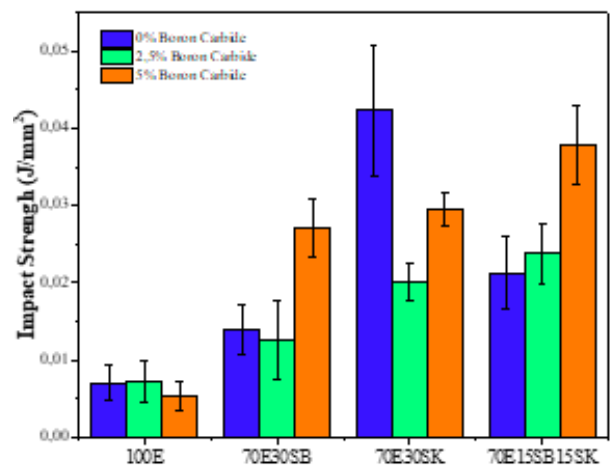


Fig. 6. Impact strength

Regardless of the effect of B₄C, the type of fibre clearly affects the impact energy absorption capacity. Glass fibre composites (70E30SK) exhibit the highest impact values in unfilled conditions due to the high modulus and strength of glass fibres, uniform fibril diameter, and generally better fibre-matrix interface quality, all of which enhance energy dissipation mechanisms such as fibre pull-out, fibre breakage, and controlled debonding [25]. Conversely, the bamboo fibre composite (70E30SB) had a lower impact value under baseline conditions due to the natural porosity and morphological heterogeneity of the fibres, which reduced the continuity of stress transfer. The hybrid system (70E15SB15SK) occupies an intermediate position, as it derives mechanical advantages from glass fibres but remains affected by the heterogeneity and moisture/non-uniformity of bamboo fibres.

3.4 Hardness

The Shore-D hardness test results shown in Fig. 7 indicate the effect of B₄C on the Shore-D hardness of composites with all types of reinforcing fibres. The highest value occurred at 2.5% B₄C, then decreased at 5% B₄C. In detail, 100E increased from 81.2 ± 0.812 (0% B₄C) to 82.8 ± 1.166 (2.5% B₄C), then decreased to 80.5 ± 2.191 (5% B₄C). Based on the data, the addition of 2.5% B₄C increased hardness across all compositions (by 4.5% in 70E30SK and 6.9% in hybrids compared to 0% B₄C). This indicates that a relatively homogeneous dispersion of B₄C filler can act as a micro-reinforcement, increasing matrix stiffness and limiting local plastic deformation in composites. Conversely, at 5% B₄C, the hardness value decreased, even approaching the initial value at 100E and

70E30SB. This indicates a tendency toward agglomeration and the formation of voids, which lead to weak composite interface bonding [23]. This phenomenon can reduce the effectiveness of micro-restraint and increase the location of damage initiation. These findings imply that there is a specific range of B₄C content that maximizes hardness, provided that B₄C dispersion is well controlled.

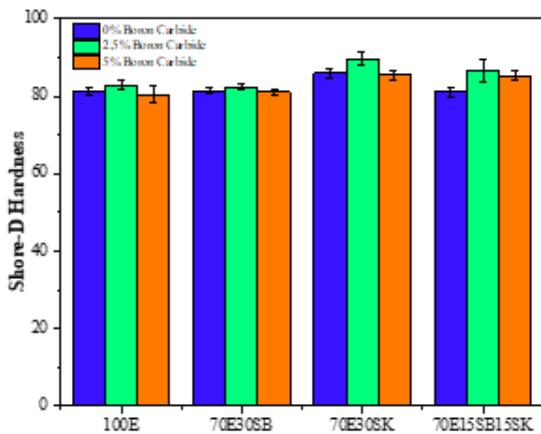


Fig. 7. Shore-D Hardness

Apart from the B₄C content, differences in reinforcing fibres also influence the hardness value of the composite. Glass fibre composites (70E30SK) showed the highest value, followed by hybrids (70E15SB15SK), while bamboo fibres (70E30SB) and pure epoxy (100E) were in the lower range. At a B₄C fraction of 2.5%, for example, the hardness values were 89.7 ± 1.749 (70E30SK), 86.7 ± 2.891 (70E15SB15SK), 82.4 ± 0.583 (70E30SB), and 82.8 ± 1.166 (100E). The superior performance of glass fibre composites is due to the high modulus of the fibres, their uniform diameter, and the sized fibre interface. This enhances the microstructural restraint against matrix plastification under the indenter [26]. Meanwhile, bamboo fibre composites have the lowest value. The lower hardness observed in bamboo fibre composites is attributed to their higher porosity, heterogeneous structure, and weaker interfacial bonding with the epoxy matrix. During Shore-D indentation, these characteristics lead to greater local deformation and reduced resistance to indenter penetration. In addition, the hydrophilic nature of bamboo fibres limits effective interfacial adhesion with the hydrophobic epoxy matrix, resulting in poor stress distribution under localized loading. This condition facilitates micro-scale deformation and reduces the overall surface hardness of the composite [27]. The hybrid system benefits from the presence of glass fibres but is still influenced by the heterogeneity and wettability of the bamboo fibre interface, placing it between the two.

3.5 Flammability

The results of the flammability test are shown in Fig. 8, 9, 10. The parameters analyzed include Char Yield (%), Limiting Oxygen Index (LOI), and Burning Rate (mm/s). The highest char yield was obtained in the 70E30SK composition, at $72.08 \pm 0.14\%$ (0% B₄C). Meanwhile, the 100E composition showed the lowest char yield, around 16.11 ± 0.52 – $19.73 \pm 0.19\%$. In general, the addition of boron carbide did not significantly increase the char yield; in fact, in some compositions, it tended to decrease the char yield. The highest combustion rate was observed in 100E, reaching 30.038 ± 2.32 mm/s (5% B₄C), while the lowest rate was observed in 70E30SK with 2.5% B₄C, at 19.094 ± 2.77 mm/s. In general, the addition of boron carbide reduced the burning rate, especially in fibre-rich compositions (70E30SK). Meanwhile, the LOI value increased consistently with the addition of B₄C. For example, in 70E30SB, the LOI increased from $29.524 \pm 0.04\%$ (0% B₄C) to $31.217 \pm 0.05\%$ (2.5% B₄C). The highest value was $45.61 \pm 0.05\%$ in the 70E30SK variation, and the lowest ranged from 23.944 ± 0.04 to $25.393 \pm 0.08\%$ in the 100E variation.

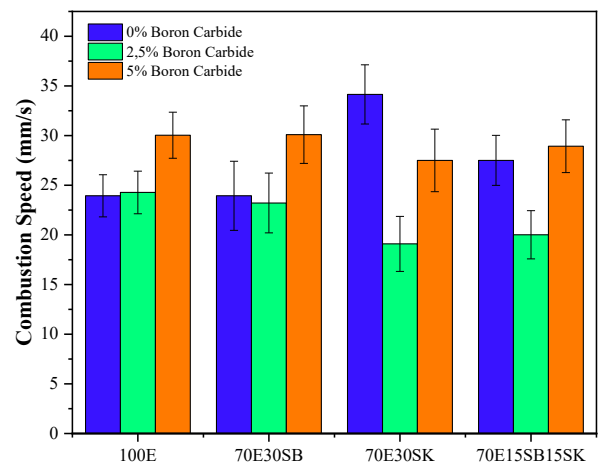


Fig. 8. Combustion rate

Based on the test results, the increase in char yield was influenced by the presence of glass fibres. This is in accordance with the literature, which states that glass fibres have inorganic and thermostable properties, enabling them to form higher char residues after combustion than pure epoxy or epoxy with bamboo fibres [28]. Meanwhile, the combustion rate results showed a significant decrease with the addition of B₄C. This indicates that the presence of B₄C helps slow down the rate of fire propagation. This is consistent with the findings of Shen [29], who reported that boron-based additives can reduce the peak heat release rate by inhibiting heat diffusion.

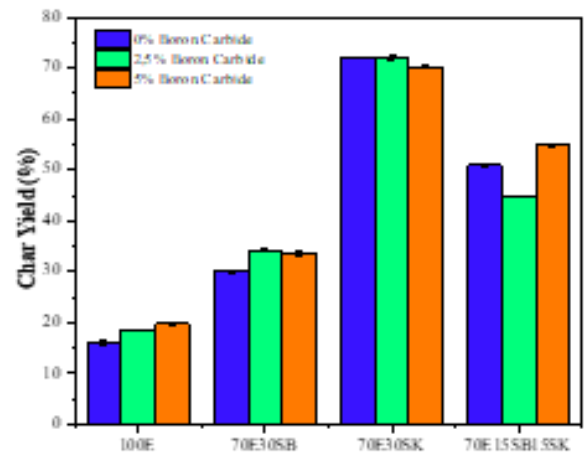


Fig. 9. Char yield

In terms of the Limiting Oxygen Index (LOI), the addition of B₄C consistently increased the LOI value in all compositions. This trend confirms that B₄C consistently improves flame resistance through the mechanisms of forming a protective oxide layer and increasing carbonization, which act as barriers to heat and oxygen diffusion [30].

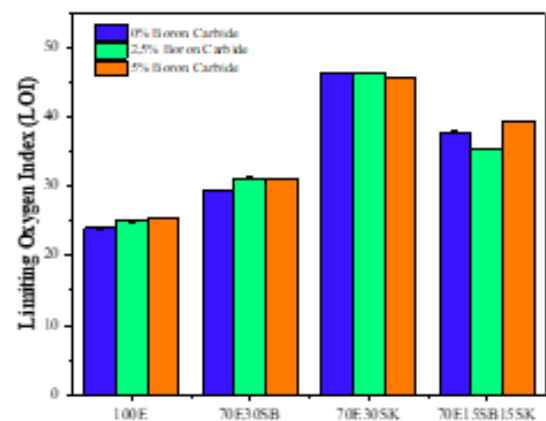


Fig. 10. LOI

3.6 Failure after tensile test

In Fig. 11, which shows the fracture of the 70E30SB 0% B₄C specimen after the tensile test, a clear fibre fracture can be seen along the bamboo fibres. This fracture indicates that the specimen has failed, as the composite's tensile strength is hindered by the weak bond between the bamboo fibres and the epoxy matrix. This dominant fibre fracture reflects the mechanical limitations of bamboo fibres as a reinforcing material, which are often more prone to failure than those of synthetic fibres such as glass fibres [31]. Additionally, interfacial debonding is also observed, indicating adhesion issues between the bamboo fibres and the epoxy matrix. This is due to the hydrophilic nature of bamboo fibres and the hydrophobic nature of the epoxy matrix, which reduces the interfacial bonding strength between the material phases [8]. This mismatch in surface properties leads to poor wetting of the bamboo fibres by the epoxy matrix, resulting in weak interfacial adhesion and inefficient stress transfer during tensile loading.



Fig.11. The macroscopic fracture observations of specimen 70E30SB 0% B₄C after tensile test

In Fig.12, which shows the fracture of the 70E30SK 2.5% B₄C specimen after the tensile test, fibre fractures are also visible, but with a more controlled pattern and less interfacial debonding.

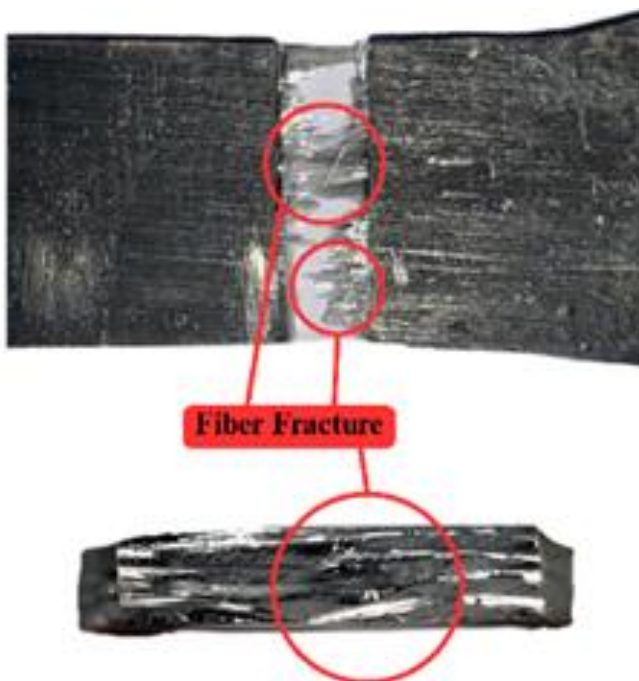


Fig.12. The macroscopic fracture observations of specimen 70E30SK 2.5% B₄C after tensile test

This indicates that the addition of 2.5% B₄C can act as a micro-reinforcer, improving the bond between the glass fibres and the matrix and thereby providing a significant increase in the tensile strength of the composite [19]. The well-dispersed addition of B₄C enhances the mechanical strength of the composite, promotes more effective load transfer, and reduces failures caused by poor tensile strength at the interface [32]. Although fibre fractures still occur, this specimen shows better resistance compared to composites without B₄C, because glass fibres have higher strength and better interfacial bonding compared to bamboo fibres[15].

3.7 Failure after Impact test

In Fig. 13, which shows the fracture of the 70E30SB 2.5% B₄C specimen after the impact test, two main failure mechanisms are clearly visible: interfacial debonding and matrix cracking. Interfacial debonding occurs due to the weak bond between the bamboo fibres and the epoxy matrix, indicating that the addition of B₄C does not fully resolve the adhesion issue between the two phases. The addition of poorly dispersed or agglomerated B₄C can create stress concentrations that lead to failure at the fibre-matrix interface [33]. Additionally, matrix cracking is observed on the fracture surface, indicating that the epoxy matrix cracked due to the impact applied during the test. This indicates that although B₄C serves as a micro-reinforcement, the still-fragile matrix structure causes the material to fail earlier under impact loading[34].

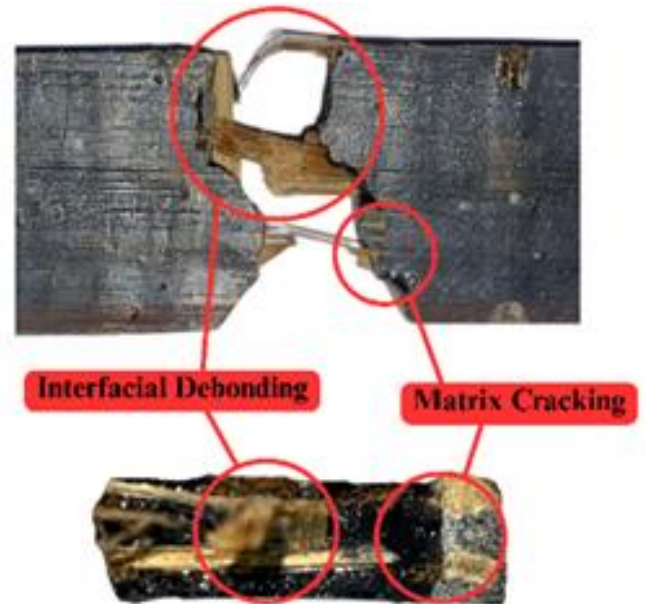


Fig. 13. The macroscopic fracture observations of specimen 70E30SB 2.5% B₄C after impact test

Conversely, in Fig. 14, which shows the fracture of the 70E30SK 0% B₄C specimen after the impact test, delamination and extensive fibre pull-out are observed. Delamination occurs between the glass fibre layers and the epoxy matrix, indicating that although glass fibres have high strength, this composite still fails at its interface. Extensive fibre pull-out is also observed on the fracture surface, indicating that glass fibres can be pulled from the matrix during impact-induced deformation. This behaviour enhances impact resistance because glass fibres possess higher strength and stiffness, allowing them to carry and redistribute impact loads more effectively. During impact, energy is dissipated through several mechanisms, including fibre pull-out, interfacial debonding, and fibre breakage, where additional energy is required to overcome interfacial friction and resist crack propagation [35]. In contrast to bamboo fibres, the more uniform structure and stronger interfacial bonding of glass fibres enable more stable load transfer and delay catastrophic failure.

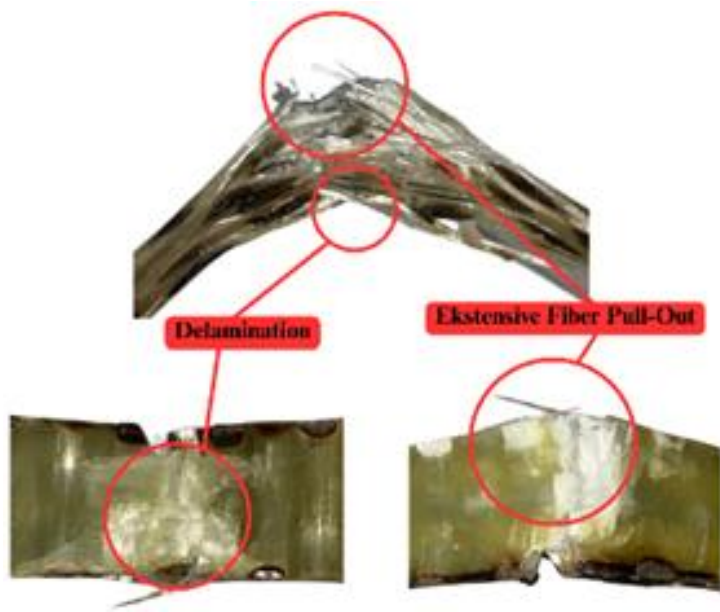


Fig. 14. The macroscopic fracture observations of specimen 70E30SK 0% B₄C after impact test

4 Conclusion

This study demonstrates that incorporating boron carbide (B₄C) into bamboo–glass fibre hybrid epoxy composites significantly influences both mechanical performance and fire resistance. The results indicate that B₄C consistently enhances fire resistance, as evidenced by increased limiting oxygen index (LOI) and reduced burning rate, particularly in glass fibre-dominant composites. In terms of mechanical properties, an optimal B₄C content of 2.5 wt% improves tensile performance and hardness, while higher filler content (5 wt%) leads to performance deterioration due to particle agglomeration and weakened interfacial bonding. The impact behaviour is influenced by fibre type, with bamboo and hybrid composites benefiting from B₄C addition, whereas glass fibre composites show more variable responses. Overall, this study highlights the importance of controlling filler dispersion and fibre–matrix interactions to achieve balanced mechanical and fire-resistant properties. The findings provide insights for the design of lightweight, high-performance, and flame-resistant composite materials for advanced engineering applications.

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