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Compressive Behaviour of Arenga Pinnata Fibre-Reinforced Epoxy Composites Enhanced with Nanosilica Modification

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ABSTRACT

Understanding the compressive behaviour and properties of fibre-reinforced polymer (FRP) composites is essential for designing effective structures and mechanical components. However, there is limited knowledge about the effect of nanosilica on the compressive properties of natural fibre composites. This gap in understanding hinders the optimization of these materials for real-world structural applications. The aim of this study is to investigate the effect of nanosilica on the compressive properties of Unidirectional (UD) continuous Arenga Pinnata Fibre Reinforced Epoxy Composites (APREC). By integrating 5 wt%, 13 wt%, and 25 wt% nanosilica into the epoxy matrix, the research evaluates how varying nanosilica content influences the compressive stress-strain behaviour. AP fibres, a lightweight, plant-based material, were utilized to develop sustainable FRP composites. The nanosilica-modified epoxy resin was mixed at 4000 rpm and 80ºC for 1 hour, and compressive tests were performed following ASTM D3410 standards. Results showed that adding nanosilica enhances the compressive strength and modulus of APREC. The 5 wt% nanosilica-modified APREC exhibited the highest compressive strength (102.053 MPa) and modulus (2.142 GPa), indicating optimal interfacial bonding. At 13 wt%, compressive strength and modulus decreased to 93.336 MPa and 1.945 GPa, respectively, while 25 wt% nanosilica further reduced performance to 70.786 MPa and 1.874 GPa. These findings suggested that 5 wt% nanosilica achieves the best balance between particle dispersion and resin wetting, while higher concentrations lead to particle aggregation and reduced mechanical properties. This study provides valuable insights into optimizing nanosilica content in APREC to enhance compressive performance in structural applications.

Keywords: Compression; arenga pinnata; nanomaterials; nanosilica

INTRODUCTION

Composite materials are made by bringing together different base materials, each with its own unique properties. Rather than blending at the microscopic level, these materials stay separate, with one acting as reinforcement and the other as the matrix. In the production of fibre reinforced polymer (FRP) composites, both natural and synthetic fibres play crucial roles as reinforcement materials (Afzaluddin et al. 2019). However, due to rising environmental concerns and a growing demand for green technology, there has been a shift from traditional synthetic fibre composites to those made with natural fibres. This transition reflects a broader commitment to renewable and sustainable materials (Alsubari et al. 2021; Jagadeesh et al. 2024; Nagaraja et al. 2024).

Researchers and manufacturers have long been drawn to natural fibres because of their many advantages. These fibres are cost-effective, biodegradable, and safe for human health, offering good mechanical properties and low density (Alsubari et al. 2021). Various natural fibres such as jute, ramie, hemp, flax, kenaf, pineapple leaf fibre (PALF), and coir have been utilized in producing fibre composites (Naveen et al. 2019; Palanisamy et al. 2024). Each natural fibre variety has unique characteristics influenced by its chemical structure and growth environment (Khan et al. 2024). This study focuses on fibres from the AP plant, chosen for its high durability and excellent resistance to sea water (Abdullah et al. 2014; Imraan et al. 2023; Ishak et al. 2013; Ku et al. 2011; Mogea et al. 1991; Parlaungan Siregar, 2005; Sapuan & Bachtiar, 2012; Ticoalu et al. 2010). These properties make AP fibres particularly advantageous compared to other natural fibres.

AP, or the sugar palm, has been a valuable resource for centuries, known for its strong and durable fibres. An ancient boat discovered on the Indonesian coast, later named "Kapal Punjulharjo" after the place it was found, used these fibres for ropes that held together key parts exposed to seawater. This discovery highlights the fibres' remarkable resilience. In the 1800s, the British East India Company planted AP trees in Penang, Malaysia, to produce durable ropes. Beyond ropes, these versatile fibres have been traditionally used for making roofs, filters, brooms, and even providing shelters for fish breeding (Mogea et al. 1991).

Modern applications of AP fibres have expanded. Researchers like Ishak et al. (2013) found that these fibres could be used for soil stabilization in road construction, effectively replacing geo-textile fibreglass. This demonstrates the fibres' strength and versatility. Additionally, AP has been used in underwater and underground cables, proving durability in harsh conditions (Parlaungan Siregar, 2005). A study by Sapuan & Bachtiar (2012) found that increasing the loading of AP fibre in the high-impact polystyrene matrix improved the mechanical properties, including the tensile modulus, of the composites. Recent studies have further explored the potential of AP fibres. For instance, Abdullah et al. (2014) investigated the thermal properties of AP fibre polymer composites, focusing on how moisture absorption affects them. Their findings suggest that these composites are suitable for various applications, showcasing the fibres' adaptability and modern relevance. From ancient maritime uses to contemporary engineering solutions, AP fibres continue to demonstrate enduring value and versatility.

Nanotechnology has emerged as a significant technology development, with researchers worldwide exploring its potential to enhance material performance and improve human life. Nanoparticles such as nanoclay, nanosilica, and carbon nanotubes have been extensively studied for their ability to enhance mechanical and physical properties, including modulus, toughness, and ductility in various materials (Kosar et al. 2008). For instance, the incorporation of nanosilica has been shown to significantly improve the mechanical properties of composites, as demonstrated by Sapiai et al. (2020). In the context of fibre composites, whether thermoplastic or thermosetting, the addition of nanoparticles is crucial for achieving superior performance. This enhancement is essential because the mechanical strength of AP reinforced epoxy composites relies on three key factors: the properties of the AP fibres, the characteristics of the epoxy matrix, and the interfacial bonding between the fibres and the matrix.

This research introduced an innovative approach by integrating surface-modified Arenga Pinnata fibres with epoxy resin enhanced by nanosilica particles to create an Arenga Pinnata fibre-reinforced epoxy composite (APREC). This study focuses on using nanosilica to enhance the mechanical properties of the epoxy resin, leading to a significant improvement in the composite's overall performance.

METHODOLOGY

MATERIALS

This research utilized AP fibres, epoxy resin (Miracast 1517), and nanosilica (Nanopox F400). The AP fibres obtained from Kuala Pilah, Negeri Sembilan, Malaysia. While, the epoxy resin Miracast 1517, which consisting of Part A (epoxy resin) and Part B (amine-curing agent), was supplied by Miracon (M) Sdn. Bhd. The epoxy and hardener were mixed in a 100:30 ratio. Spherical silica

nanoparticles, Nanopox F400, provided by Evonic Industries, Germany, were used to modify the epoxy resin. These nanoparticles, with a mean size of about 20 nm, were in the form of a colloidal sol (40 wt.%) in epoxy resin. Three different weight percentages of nanosilica (5, 13, and 25 wt.%) were used in this study (Sapiai et al. 2015).

The nanosilica-modified APREC was fabricated using 25 vol% AP fibres and three distinct nanosilica concentrations (5 wt.%, 13 wt.%, and 25 wt.%) blended into the epoxy. The epoxy resin was blended with nanosilica using a magnetic stirrer at 400 rpm and 80°C for 1 hour.

The resulting mixture was then transferred to a vacuum oven, where it was subjected to 0.07 MPa load and maintained for 1 hour to eliminate air bubbles. Subsequently, the mixture was then mixed with hardener and was then poured into a mold containing the AP fibres. The APREC was fabricated using a hand lay-up technique with a square mold as illustrated in Figure 1 and was cured for 24 hours under pressure using a cold press machine, as described in Khalid et al. (2017). Table 1 tabulates the specimens used in this present study.

COMPRESSION

Compression tests were carried out to evaluate the ultimate compressive strength, strain-at-failure, and compressive modulus of both APREC and nanosilica-modified APREC. The specimens and testing procedures for compression evaluation were prepared in accordance with ASTM D3410 (International, 2021). The compression test was conducted on a rectangular specimen measuring 110 mm in length, 9.8 mm in width, and 4 mm in thickness. The test setup, shown in Figure 2, utilized a jig mounted on the Instron 3382 Universal Testing Machine. Bluehill 2 software was utilized to set up system parameters and record the applied load and compressive extension. The specimen was positioned as shown in Figure 2(c), and the test was carried out at a crosshead speed of 1 mm/min.

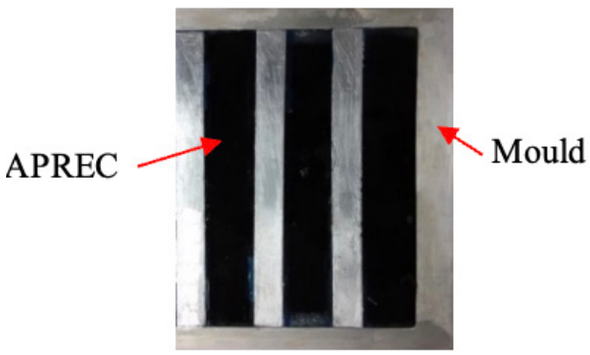

FIGURE 1. Cured specimen in mould

TABLE 1. Specimens designated for the compression test

No	Specimens	Designated
1	Pure Epoxy	PE
2	Epoxy + 5wt.% nanosilica	5NSE
3	Epoxy + 13wt.% nanosilica	13NSE
4	Epoxy + 25wt.% nanosilica	25NSE
5	UD APREC	APREC
6	UD APREC 5wt.% nanosilica	5NSAPREC
7	UD APREC 13wt.% nanosilica	13NSAPREC
8	UD APREC 25wt.% nanosilica	25NSAPREC

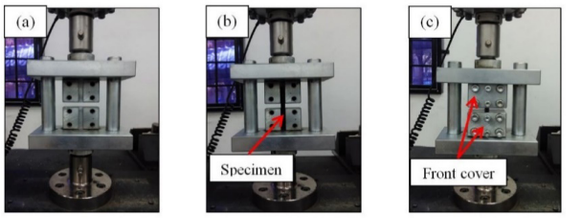

FIGURE 2. Configuration of the compressive test jig: (a) without the specimen, (b) with the specimen, and (c) with the specimen and front cover in place

The compressive stress, strain, and modulus were calculated from the load and extension data collected during the test. The following properties can be derived from a compression test:

Compressive stress, σ_c, is defined as the compressive load (force), F, divided by the original cross-sectional area, A, within the gauge length.

$$\sigma_c = \frac{F}{A} \tag{1}$$

Compressive strain, ε_c, is the change in length, Δl, divided by the original length, l_o, of the gauge.

$$\varepsilon_c = \frac{\Delta l}{l_o} \tag{2}$$

Compressive modulus, E_c, is the ratio of compressive stress to compressive strain.

$$E_c = \frac{\sigma_c}{\varepsilon_c} \tag{3}$$

Compressive strength, σ_{cu}, is the maximum compressive stress reached before the specimen fails.

RESULTS AND DISCUSSION

COMPRESSION ANALYSIS

A compression test was conducted to assess the influence of nanosilica content on the compressive behaviour of epoxy resin and APREC composites.

Figure 3 illustrates the typical compressive stress-strain curves for pure epoxy (PE and epoxy modified with various nanosilica contents (5NSE, 13NSE, and 25NSE. The curves for the nanosilica-modified specimens displayed higher initial slope gradients compared to pure epoxy, indicating an increase in stiffness. Specifically, 5NSE had the least steep slope among the modified specimens, suggesting it exhibited slightly lower stiffness than the 13NSE and 25NSE composites. This suggests that while the incorporation of nanosilica improves the overall compressive stiffness of the epoxy resin, the optimal concentration for stiffness enhancement may not be reached at 5%, as higher concentrations (13% and 25% continue to show increased stiffness. Therefore, the stiffness of the composite improves with nanosilica, but the performance varies depending on the weight percentage level used.

The compressive stress-strain curve for pure epoxy revealed the lowest compressive stress at failure (approximately 20% strain while showing the highest strain at failure. In contrast, the 25NSE specimen exhibited the highest stress at failure but the lowest strain at failure.

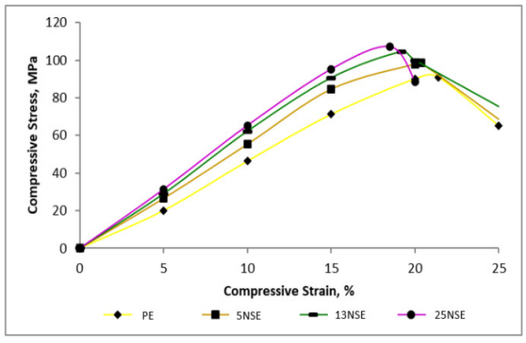

FIGURE 3. The effect of incorporation of nanosilica to the compressive stress-train curve in Epoxy

Figure 4 depicting the compressive stress-strain curves for APREC composites with varying nanosilica content. Initially, the unmodified APREC composite (0% nanosilica) demonstrates standard stress-strain behaviour, but it experiences a less steep increase in stress as strain rises, suggesting that while the material can withstand initial compression, its performance deteriorates at higher strains. This behaviour is typical for composites with limited reinforcement. The 5% nanosilica composite shows a marked improvement in compressive performance, as evidenced by a steeper stress-strain curve. This suggests that incorporating a small amount of nanosilica enhances the stiffness of the composite, allowing it to withstand higher compressive stress at lower strain levels which occurred around 20% compressive strain. This improvement is likely due to the nanosilica's ability to strengthen the resin matrix and improve fibre-matrix interaction, resulting in a more robust composite structure. However, the 13% nanosilica composite shows a slight decline in compressive strength at higher strains compared to the 5% composite. This could indicate that while the initial incorporation of nanosilica strengthens the matrix, the optimal concentration has been exceeded. At higher concentrations, nanosilica particles may disrupt the resin's wetting of the fibres, causing weakened interfacial bonding and diminishing the composite's ability to sustain stress at higher strains.

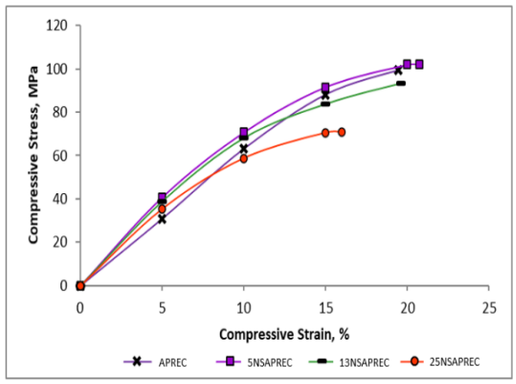

FIGURE 4. The effect of different nanosilica content to the compressive stress-train curve of APREC composite

The 25% nanosilica composite shows a significant drop in compressive performance at approximately between 10% to 15% compressive strain, particularly at higher strains, confirming that excessive nanosilica disrupts the material's structural integrity. The resin likely cannot adequately wet the fibres due to the high nanosilica concentration, leading to poor interfacial bonding and reduced mechanical performance under stress. In conclusion, the graph demonstrates that while nanosilica can significantly enhance the compressive properties of APREC composites, its effectiveness is highly dependent on the nanosilica content. A moderate amount (5%) of nanosilica optimizes the composite's strength, while higher concentrations (13% and 25%) result in diminished performance, emphasizing the need for careful control of nanosilica content in composite material design.

Figure 5 shows the compressive modulus of the epoxy specimens derived from Figure 3. There is a clear positive trend observed between the amount of silica content and

the compressive modulus. As the percentage of nanosilica increased from 0% (pure epoxy) to 25%, the compressive modulus also increases which suggests that the addition of nanosilica content enhances the stiffness of the epoxy material. The 5NSE specimen exhibited a 45.02% improvement in resistance to compressive load compared to PE. The 13NSE specimen showed a 54.77% improvement, while the 25NSE specimen achieved a 69.96% increase. These results indicate that incorporating up to 25 wt.% nanosilica to Miracast 1517 epoxy resin greatly improves its compressive modulus, attributed to the uniform dispersion of nanosilica particles within the epoxy matrix (Jumahat et al. 2012). This suggests that nanosilica is effective in enhancing the mechanical properties of epoxy, potentially making it more suitable for applications requiring higher stiffness.

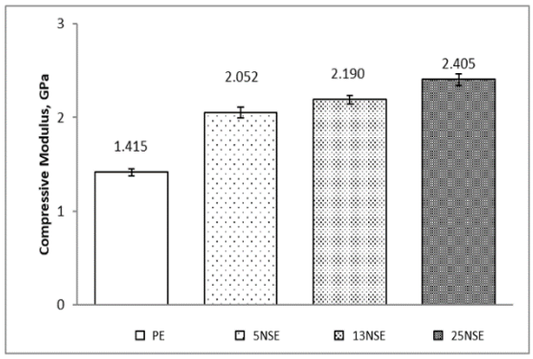

FIGURE 5. The effect of different nanosilica content to the compressive modulus of pure epoxy

The compressive modulus of the 5NSAPREC, 13NSAPREC, and 25NSAPREC specimens were higher than that of the APREC specimen (Figure 6). However, the 13NSAPREC and 25NSAPREC specimens showed a lower compressive modulus compared to the 5NSAPREC specimen. The reduction of compressive modulus at higher percentage of nanosilica content is due to improper wetting and dispersion of the nanosilica particles in the matrix, causing agglomeration and defects that compromise the composite's structure (Nasser et al. 2022). This suggests that adding more than 5 wt.% nanosilica to APREC did not further improve its compressive modulus.

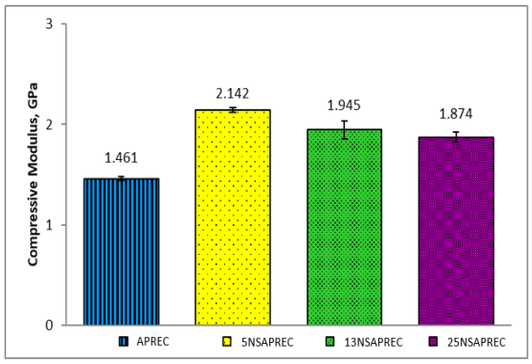

FIGURE 6. The effect of incorporation of different nanosilica content to the compressive modulus of APREC composite

Table 2 shows the compressive strength and strain for pure epoxy, nano-modified epoxy, APREC, and nano-modified APREC. The 5NSE specimen exhibited an 8.23% increase in compressive strength compared to pure epoxy, while the 13NSE and 25NSE specimens showed improvements of 14.85% and 17.73%, respectively. However, the compressive strain for the 5NSE, 13NSE, and 25NSE specimens decreased by 4.78%, 10.24%, and 13.56%, respectively, indicating that higher nanosilica content enhances strength but reduces strain tolerance.

TABLE 2. The effect of incorporation of nanosilica in epoxy and APREC to the compressive strength and compressive strain

Specimens	Designated	Compressive Strength (MPa)	Compressive Strain (%)
Epoxy	PE	90.980 ± 5.453	21.403 ± 1.532
	5NSE	98.466 ± 2.040	20.380 ± 1.325
	13NSE	104.491 ± 2.342	19.211 ± 0.085
	25NSE	107.114 ± 2.714	18.500 ± 1.189
Composite	APREC	99.327 ± 2.492	19.426 ± 1.615
	5NSAPREC	102.053 ± 2.846	20.742 ± 0.854
	13NSAPREC	93.336 ± 6.109	19.211 ± 0.085
	25NSAPREC	70.786 ± 6.539	16.009 ± 2.213

The addition of 5 wt.% nanosilica to APREC specimens resulted in a 2.74% increase in compressive strength. However, incorporating 13 wt.% and 25 wt.% nanosilica into APREC led to a decrease in compressive strength of 6.03% and 28.73%, respectively. A slight increase of 6.77% in compressive strain was observed in the 5NSAPREC specimen compared to the APREC specimen. Further addition of nanosilica (13 wt.% and 25 wt.%) caused the compressive strain to drop due to poor interfacial bonding caused by insufficient epoxy content (Manap et al. 2015) to properly coat the fibres and nanosilica.

MICROSTRUCTURAL ANALYSIS

A scanning electron microscope (SEM) image of the 5NSAPREC specimen after compression testing was shown in Figure 7. The image reveals that the AP fibres were detached from the epoxy matrix, although the fibre surfaces remained, its surfaces remained undamaged and intact after the test. This showed that the hydrophilic AP fibres and the hydrophobic epoxy resin had poor interfacial bonding (Kabir et al. 2012; Siregar et al. 2021).

The SEM image of the 5NSAPREC composite after load application reveals the AP (Arenga pinnata) fibres in good condition, showcasing the intact structure and resilience of the material under stress. Despite the applied load, the fibres remain well-preserved with no visible cracks or significant damage, indicating that the composite maintains its structural stability. The image emphasizes the strong fibre-matrix interaction, suggesting that the incorporation of 5% nanosilica enhances the performance of the APREC composite by improving the bonding between the fibres and the matrix. The absence of fibre damage under stress is a positive indication of the composite's durability, demonstrating that the nanosilica content helps distribute stress more evenly and enhances the overall mechanical properties. The scale bar of 1 mm further highlights the size of the features, providing context for understanding the material's microstructure. Overall, the 5NSAPREC composite demonstrates promising performance under load without compromising fibre integrity.

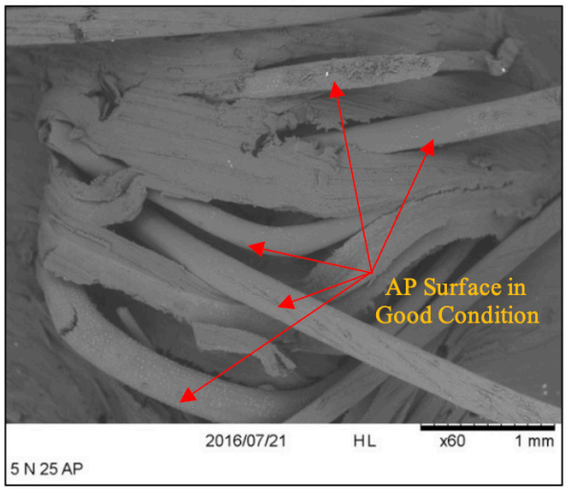

FIGURE 7. SEM image of 5NSAPREC after load applied

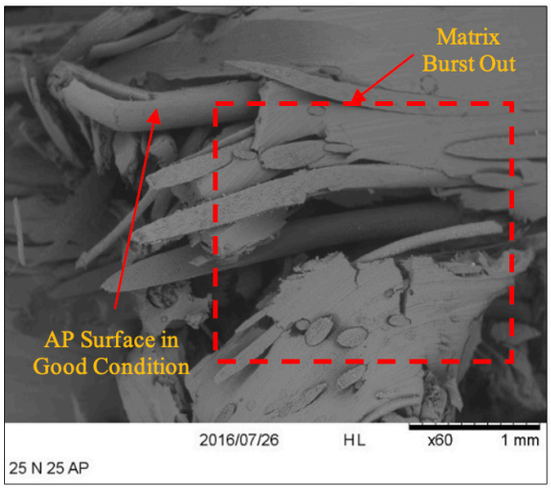

FIGURE 8. SEM image of specimen 25NSAPREC after load applied

The SEM image of the 25NSAPREC specimen after compression testing was illustrated in Figure 8. This image was examined to investigate why increasing the nanosilica content beyond 13 wt.% resulted in a decrease in compressive properties. The image reveals that the epoxy matrix fractured after the test, indicating that the epoxy became significantly more brittle compared to APREC specimens without nanosilica and those with 5 wt.% nanosilica (Figure 7). The AP fibres also seemed to detach from the epoxy matrix, showing a lack of interfacial interaction between the fibre and matrix (Jumahat et al. 2017).

The SEM image of the 25NSAPREC composite after load application shows the AP fibre surface in good condition, but the epoxy matrix exhibits a noticeable burst-out, as highlighted in the red dashed box. This burst-out suggests that under the applied load, the epoxy matrix was unable to maintain its structural integrity, likely due to stress concentration or excessive nanosilica content that may have disrupted the matrix's bond with the fibres (Jumahat et al. 2017). The burst-out indicates localized failure in the matrix, potentially compromising the overall mechanical performance of the composite.

In contrast, the 5NSAPREC composite, as seen in the previous image, shows the AP fibre surface remaining in good condition, with no visible matrix failure or burst-out. This suggests that the 5% nanosilica content provided a better balance between fibre and matrix interaction, enhancing the material's ability to withstand applied stress without significant damage. Therefore, while 5NSAPREC shows improved performance, the higher nanosilica content in 25NSAPREC appears to cause some matrix failure under load.

CONCLUSION

The influence of varying nanosilica content on the compressive properties of unidirectional (UD) APREC composites was investigated, revealing significant changes in the material's performance. The addition of 5 wt.% nanosilica resulted in the most considerable enhancement in compressive strength, highlighting the positive effect of nanosilica at moderate concentrations. However, when the nanosilica content surpassed 5 wt.%, a decline in strength was observed. This reduction can be attributed to the excessive nanosilica particles interfering with the resin's ability to adequately wet the AP fibres, thereby compromising the overall composite strength. Furthermore, the compressive modulus of APREC improved with increasing nanosilica content up to 5 wt.%, but this trend reversed beyond this concentration. At higher nanosilica levels (13 wt.% and 25 wt.%), the properties of the fibres and the bonding between the fibres and the matrix became more influential. Incomplete resin wetting at these higher nanosilica concentrations resulted in weakened interfacial bonding, negatively affecting compressive modulus. As a result, the APREC composites with 13 wt.% and 25 wt.% nanosilica exhibited lower mechanical performance compared to the 5 wt.% nanosilica composites. Overall, the findings indicate that a balanced nanosilica content is crucial for optimizing the compressive properties of APREC composites, with 5 wt.% being the most effective concentration.

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DECLARATION OF COMPETING INTEREST

None.

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