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**RESEARCH ARTICLE**

# MORPHOLOGICAL PROPERTIES OF EPOXY COATED BAMBOO FIBERS BEFORE AND AFTER SEAWATER EXPOSURE

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**Abstract.** Bamboo, recognized as a sustainable construction material, shows great potential for use in challenging environments such as seawater. However, its inherent hydrophilicity limits its application in such conditions. Therefore, enhancing the water resistivity of bamboo through the application of a polymeric coating is crucial to limit seawater absorption. This research aims to examine the effects of seawater on the morphological characteristics of bamboo fibers coated with epoxy, considering variations in seawater concentration. The bamboo samples were subjected to heat treatment at 170°C and manually coated with two layers of epoxy. They were then submerged in seawater at concentrations of 100%, 50%, and 0% for a duration of 21 days. Field emission scanning electron microscopy (FESEM) analysis revealed that the double epoxy coatings provided complete surface coverage, characterized by continuity, uniformity, and smoothness. Additionally, the coating was observed to be intact and free of any damage on both the bamboo surface and the cross-section before immersion. However, samples exposed to 100% seawater exhibited significant coating degradation, characterized by surface deterioration and separation of the coating. Coating detachment was observed across all samples, with higher salinity levels resulting in more extensive damage. These findings highlight the role of epoxy coatings in enhancing bamboo's resistance to marine conditions, although their protective effects may be limited to short-term applications in seawater

**Keywords:** Bamboo, seawater, epoxy, coating.

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## 1. INTRODUCTION

Bamboo is increasingly recognized as a viable alternative to traditional wood in construction, primarily due to its remarkable mechanical properties [1]. It exhibits a tensile strength of 159 MPa, flexural strength of 120 MPa, compressive strength of 52 MPa, and shear strength of 9 MPa, making it an attractive option for builders seeking durable materials [2]. In addition to its impressive mechanical strengths, bamboo's rapid growth rate, reaching maturity in just 3 to 5 years, cost-effectiveness and abundant availability, makes it a highly appealing and popular choice in the construction sector [3, 4]. However, despite these advantages, bamboo's inherent hydrophilic nature limits its applications. Being a cellulose fiber rich in hydroxyl groups, bamboo is susceptible to moisture exposure [5, 6], which can lead to cracking and deformation that adversely affects its mechanical properties [7, 8]. To mitigate moisture-related issues bamboo is often treated with polymeric coatings that provide effective barriers against water penetration [9].

The coating system serves as a promising initiative that acts as an effective physical barrier on substrates in aggressive environments, thereby enhancing their lifespan [10]. Increasing interest among researchers in applying polymeric coatings on natural fibers aims to improve water resistivity. The interfacial adhesion between fiber and matrix plays a crucial role in reducing water permeability by minimizing the gaps between them [11]. Among various coatings, epoxy is recognized as the most efficient protective barrier due to its superior mechanical strength, chemical resistance, and durability against wear and tear, while also providing aesthetic appeal [10, 12]. Currently, epoxy resin is extensively utilized in surface coatings and represents an economically viable option for regular structural maintenance [12]. When combined with natural fibers, epoxy resin effectively substitutes lignin, enhancing the bonding of fiber cells due to its strong cohesion and dense molecular structure. Research indicates that integrating surface modification with epoxy coating yields optimal performance by achieving strong fiber-matrix interfacial bonding [13]. However, the performance of epoxy-coated bamboo in seawater remains largely unexplored, particularly concerning the adhesion of the coating.

Seawater presents a harsh environment that can significantly degrade coated surfaces due to prolonged exposure. Its alkaline nature, with an average density of 1.025 g/cm$^3$, and salinity levels ranging from 0.6% to 4.8%, with an average of 3.5%, contribute to the challenges faced by materials exposed to marine conditions [14]. The chloride ($Cl^-$) and sulfate ($SO_4^{2-}$) ions in seawater constitute a substantial portion of its salinity, accounting for 46.6%–77.5% and 4.9%–19.1% of total salts, respectively. Extended exposure to saltwater can increase the acidity within bamboo, compromising its structural integrity [15]. Moreover, natural fibers submerged in seawater are subject to osmotic effects influenced by salt concentration, which can lead to significant changes in their surface characteristics, such as the development of an orange-brown fuzzy texture due to repeated exposure [15]. As water evaporates, salt accumulates on the fiber surface, initiating degradation processes that affect the middle lamella and promote fiber separation.

Therefore, this study aimed to explore the morphological properties of epoxy-coated bamboo interfaces before and after exposure to various concentrations of seawater, aiming to evaluate the impact of this harsh environment on the integrity of the epoxy coating.

## 2. MATERIALS AND METHODS

### *2.1 Raw materials*

A matured 3-4 years old *Gigantochloa scortechinii* culms were selected and purchased from Forest Research Institute Malaysia (FRIM), Kepong, Selangor. Epoxy Bisphenol A Diglycidyl Ether (DGEBA) and hardener (Modified Polyamine) are shown in Figure 1. The epoxy and hardener are EPOXEN CP362 Part A and EPOXEN CP362 Part B manufactured by Oriental Option Sdn.Bhd and supplied by Vistec Technology Services Sdn. Bhd. [16]. The physical characteristics of epoxy and hardener are represented in Table 1.

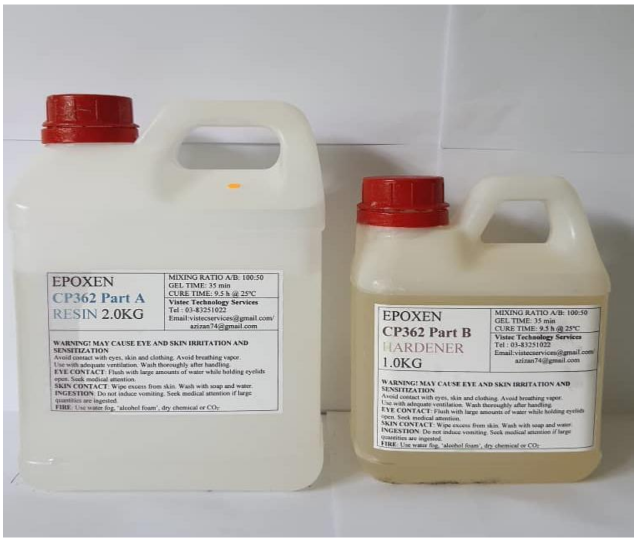


**Figure 1:** Epoxy CP 362

**Table 1:** Physical characteristics of both epoxy and hardener [16]

| Chemical Type | Viscosity (cps) | Colour | Gel Time at 25 ºC | Post Cure at 25 ºC | Final Viscosity (cps) |
|---|---|---|---|---|---|
| **Epoxy DGEBA (Epoxy)** | 13 000 | Transparent | 35 Minutes | 9.5 Hours | 8500 |
| **Modified Polyamine (Hardener)** | 400 | Transparent | | | |

### *2.2 Bamboo strips preparation*

Firstly, the bamboo culms were air dried for 7 days to eliminate moisture. The strips were prepared in dimensional sizes of 200 mm x 20 mm x 5 mm. Then the strips were oven dried in accordance to ASTM D4442-92. The bamboo strips were oven-dried at 105 ±2 ºC until reaching a constant weight [17] which took approximately 48 hours. Thereafter, the bamboo strips were heat treated at 170 ºC for 4 hours. After heat treatment, the strips were conditioned at 20 ±5 ºC and 65% relative humidity (RH) until a constant mass was reached.

### *2.3 Epoxy coating process*

The strips were epoxy coated referring to ASTM D16. Before beginning the coating process, the strips were smoothened by using silicon carbide abrasive paper (1000 Cw) to make a smoother surface and free of contaminants that increase the bonding between epoxy matrix and the strip [18]. The mixing ratio for epoxy and hardener is 2:1 and the epoxy were manually stirred until it gets warm. The coating was manually coated with a brush to the front and side face of the strip (the back was left uncoated) with 1 dip and three coats [18] as shown in Figure 2(a). After top, bottom and side face of section A was coated, the bamboo strips were leaned on a plastic covered wall for the drying process as shown in Figure 2(b). The coated bamboo strips were air dried at 23±2 ºC for a day. Then the next day, the coating continued with side B and dried. To continue coating with double layer, the same coating sequence was followed. Approximately it takes 4 days to complete double coating.

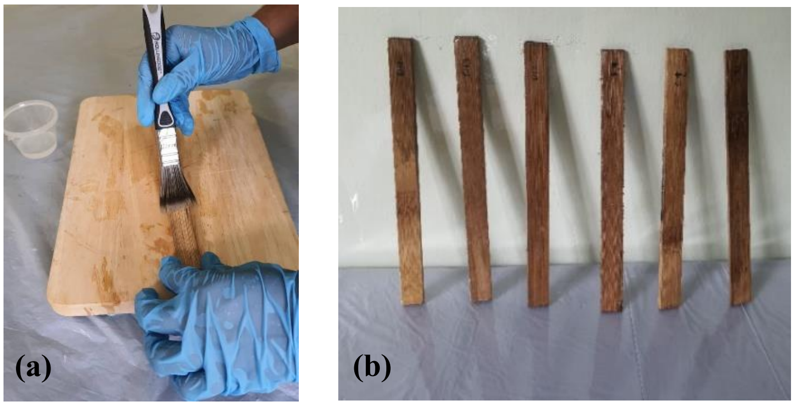


**Figure 2: (**a) Epoxy coating process and (b) drying process

### *2.4 Immersion method*

After the epoxy coating had dried, the strips were subjected to immersion. The varied seawater salinity was prepared as shown in Table 2. The strips were immersed in the prepared seawater concentration for 21 days.

**Table 2:** Details of the prepared seawater with varying salinity levels

| Seawater concentration (%) | Types of water | Quantity, ml | Salt content (%ppt) | pH | Coded |
|---|---|---|---|---|---|
| 100 | Natural sea water | 1600 | 26.0 | 7.51 | SC100% |
| 50 | Diluted sea water with distilled water | 800+800 | 13.6 | 7.57 | SC50% |
| 0 | Pure distilled water | 1600 | 0 | 7.0 | SC0% |

### *2.5 Field emission scanning electron microscopy (FESEM)*

To evaluate the degradation effects of varying seawater concentrations, the surface morphology of epoxy-coated bamboo was examined using Field Emission Scanning Electron Microscopy (FESEM) before (as a reference) and after immersion. Prior to imaging, the bamboo samples were coated for 2 minutes using a Quorum Q150RS sputter coater (Figure 3(a)) to improve conductivity and the samples after coating is shown in Figure 3(b). The FESEM analysis was conducted using a ZEISS FESEM (Carl Zeiss Sdn. Bhd.) in high vacuum mode at an accelerating voltage of 20 kV (Figure 3(c)). The morphological characterization was performed at the i-CRIM Laboratory, Universiti Kebangsaan Malaysia (UKM), Malaysia.

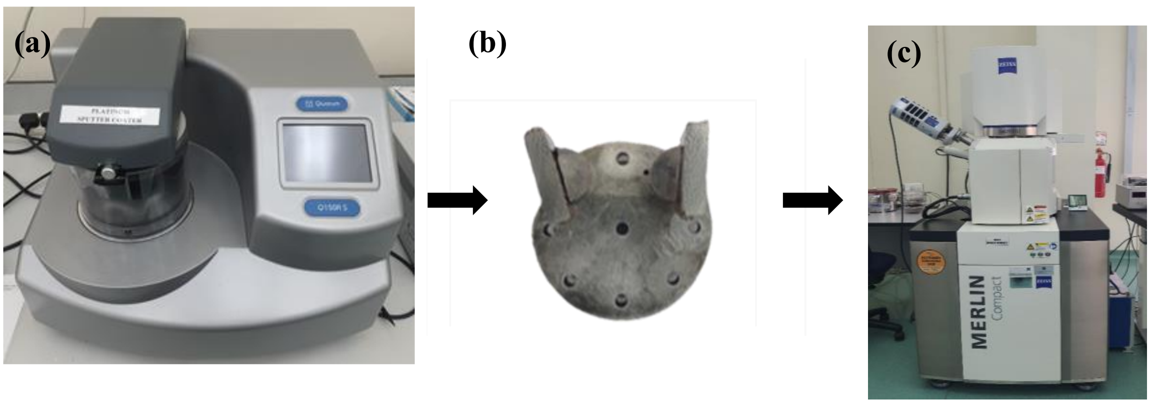


**Figure 3:** (a) Sputter coating machine, Quorum / Q 15 ORS, (b) Bamboo sample after sputter coated with platinum and (c) Field emission scanning electron microscopy, ZEISS machine

## 3. RESULTS AND DISCUSSION

This section investigates the morphology of the epoxy coated bamboo strip before and after immersion in varied concentrated seawater. The before immersion analysis focused on coating uniformity and adhesion whereas the after-immersion analysis examines the effects of varied seawater induced degradation.

### a) Before seawater immersion- Epoxy coating uniformity and adhesion

Figure 4 displays the (a) bamboo surface and (b) cross section coated with double layer epoxy before immersing in seawater. The morphology confirms that the interface has more uniform coating coverage, although a few bubbles were observed, similar to findings reported by [19]. This observation suggests that applying two layers of epoxy resin enhances its permeability and distribution uniformity on the surface. From the cross-section view, the fiber-matrix adhesion remains intact, showing no signs of peeling or inadequate coverage. The double-layer application appears to enhance the coating's effectiveness and overall surface protection before immersion.

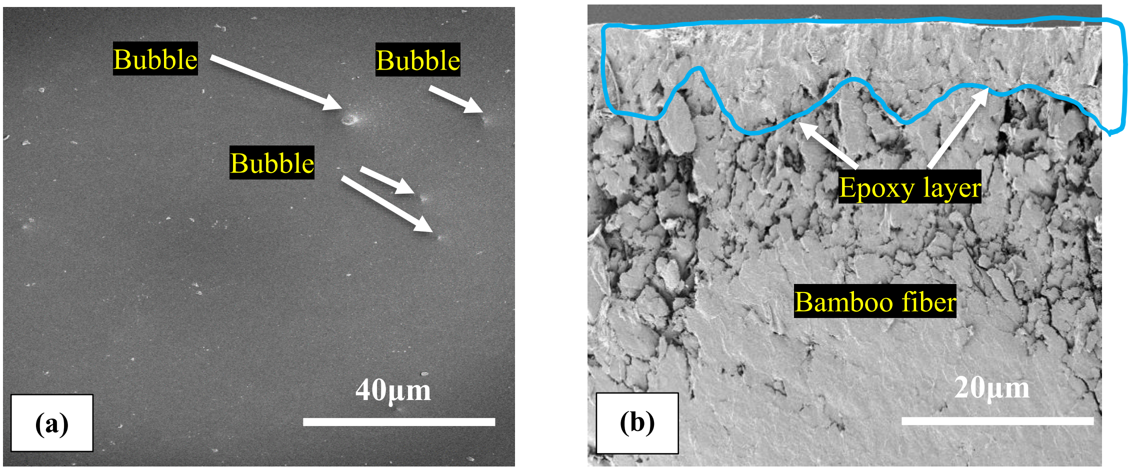


**Figure 4:** Microstructure of epoxy coated bamboo strips (a) top surface and (b) cross section

### b) After seawater immersion – Surface coating degradation

Figures 5(a) and 5(b) illustrates the morphological changes in bamboo strips after a 21-day immersion in varying seawater concentrations. The strips exposed to 100 % seawater concentration (SC100%) exhibited the notable deterioration, with their coated surfaces displaying dark spots, salt deposits, and small particles. These dark areas indicate changes in surface topography and material composition, resulting from extended exposure to salt and various marine chemicals [20].

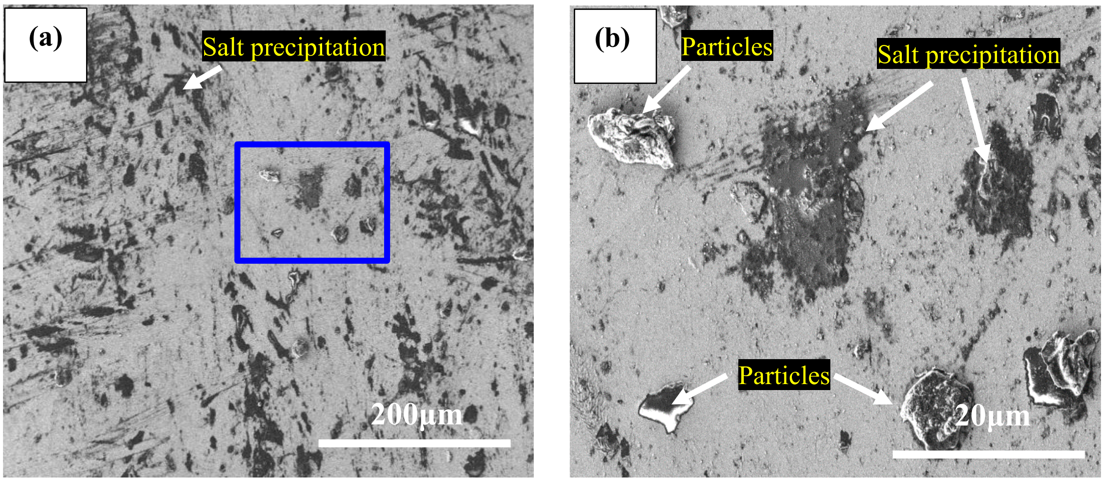


**Figure 5:** Microstructure of epoxy coated bamboo strips after immersing in SC100%

Figures 6(a) and 6(b) depicts the epoxy-coated interface of bamboo strips exposed to 50 % seawater concentration (SC50%). While the coated surface appears relatively uniform, the epoxy coating shows evidence of damage, suggesting that even partial seawater exposure affects the protective layer. The coating degradation is visible in the form of emerging microcracks. These microcracks, along with rough patches and potential delamination of the epoxy layer, are typical indicators of coating deterioration, as noted by [20].

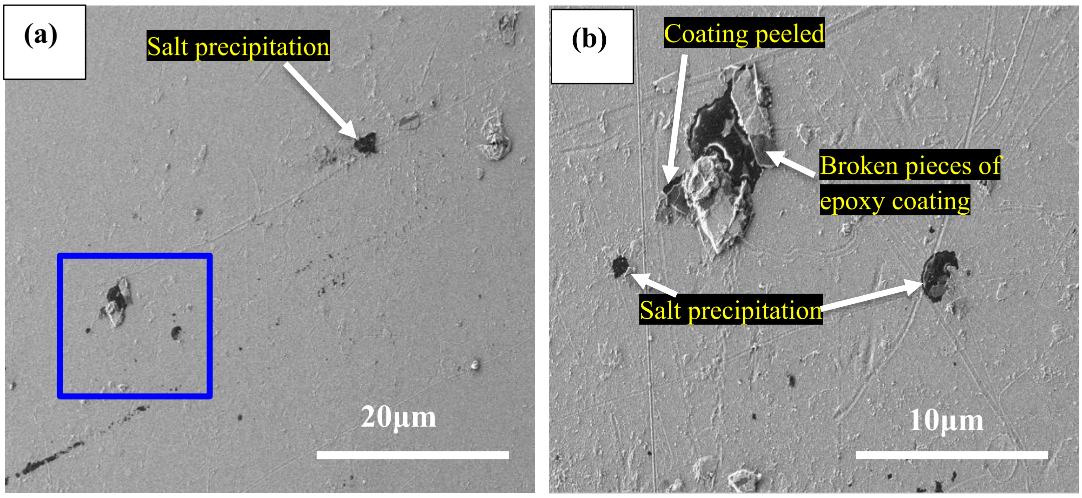


**Figure 6:** Microstructure of epoxy coated bamboo strips after immersing in SC50%
(a) magnification 300x and (b) magnification 1.0x

The coating on bamboo strips exposed to 0 % seawater concentration (SC0%), as shown in Figure 7(a) and 7(b), remains intact but displays signs of microstructural damage and contains some particulate matter. Despite these minor imperfections, the coating maintains its continuity across the surface.

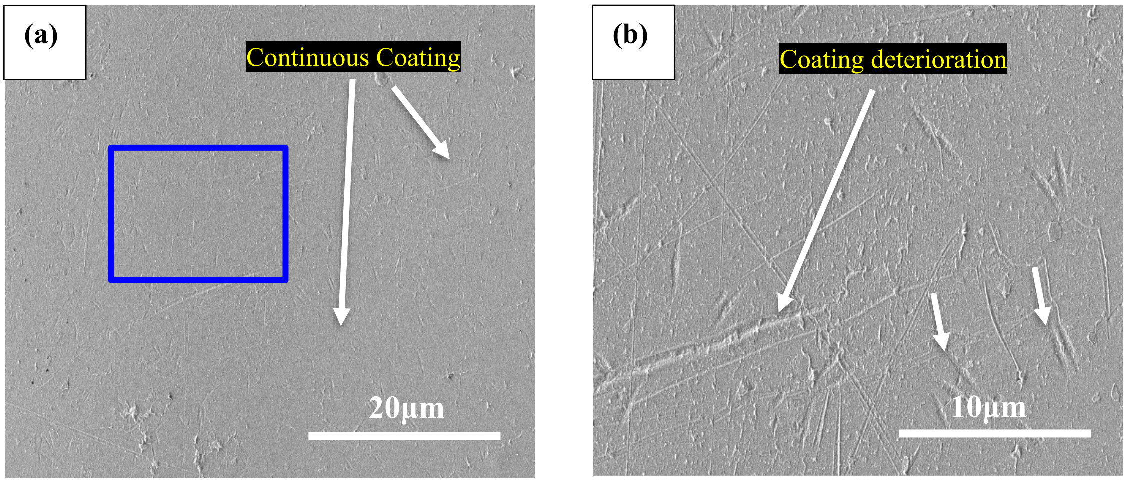


**Figure 7:** Microstructure of epoxy coated bamboo strips after immersing in SC0% (a) magnification 100x and (b) magnification 300x

### c) After seawater immersion – Epoxy coat debonding

Figures 8(a) and 8(b) depict both epoxy coating detachment and fracturing observed in the strips from SC100%. All bamboo strips showed some level of epoxy coating detachment from their surfaces following the immersion period.

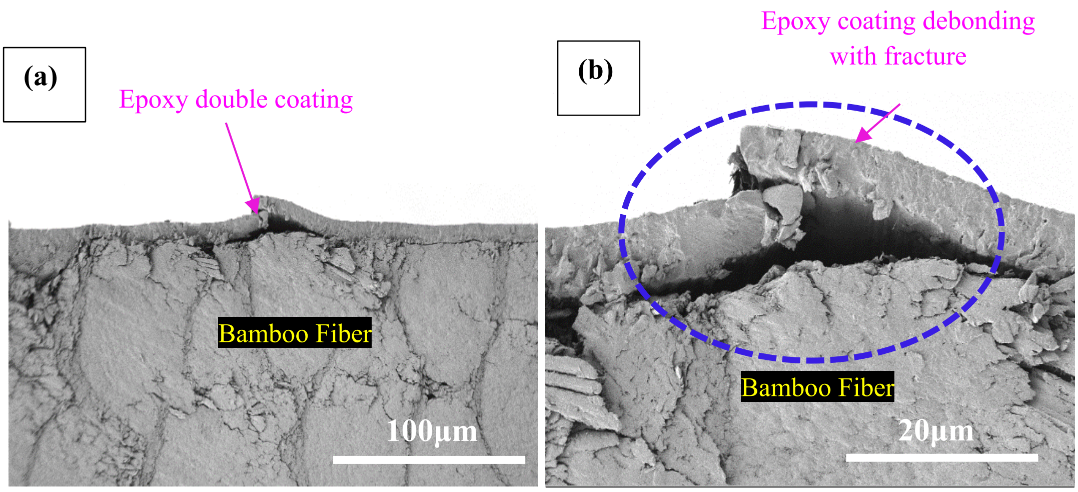


**Figure 8:** Cross-sectional micrograph of epoxy coated bamboo strips after immersing in SC100% (a) magnification 100x and (b) magnification 300x

In contrast, Figures 9(a) and 9(b) demonstrate that the strips immersed in SC50% exhibited only coating detachment without any breakage.

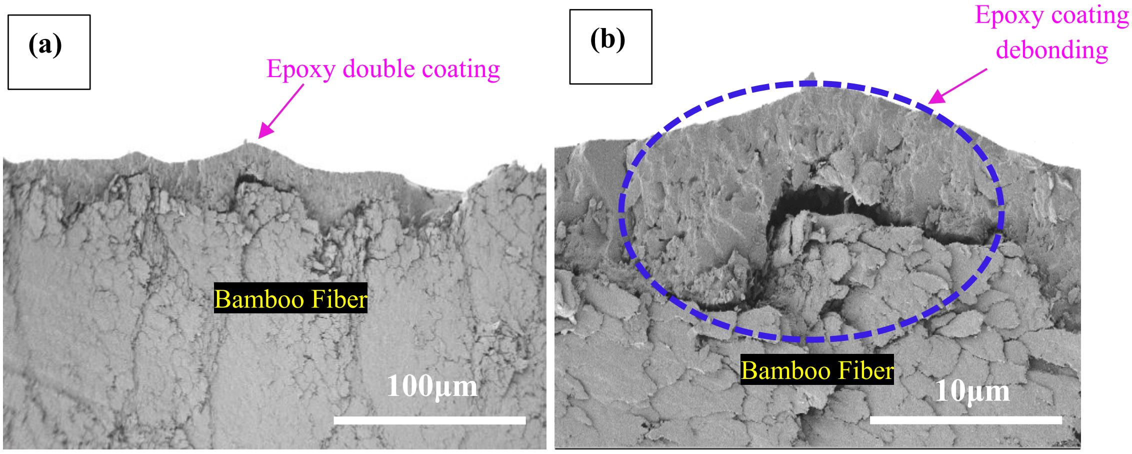


**Figure 9:** Cross-sectional micrograph of epoxy coated bamboo strips after immersing in SC50% (a) magnification 100x and (b) magnification 400x

Figures 10(a) to 10(b) highlight that the bamboo strips from SC0% samples exhibited the most severe coating debonding, characterized by edge peeling and significant fiber swelling. This behavior is attributed to the highest water absorption observed in SC0% samples compared to SC50% and SC100%. Previous studies, such as those by [21, 22], also reported similar findings, indicating higher water absorption in distilled water environments. The difference in water absorption can be explained by the distinct properties of distilled water and seawater. According to [23] and [21], seawater has higher hardness due to its ionic content, which slows down water transport into bamboo fibers. The salt ions present in seawater clog the bamboo's microstructure and stabilize the epoxy coating, thereby limiting water absorption. In contrast, distilled water lacks these salts, allowing unrestricted water transport into bamboo's porous structure. This leads to excessive water absorption in SC0% samples, causing fiber swelling and exacerbated coating detachment.

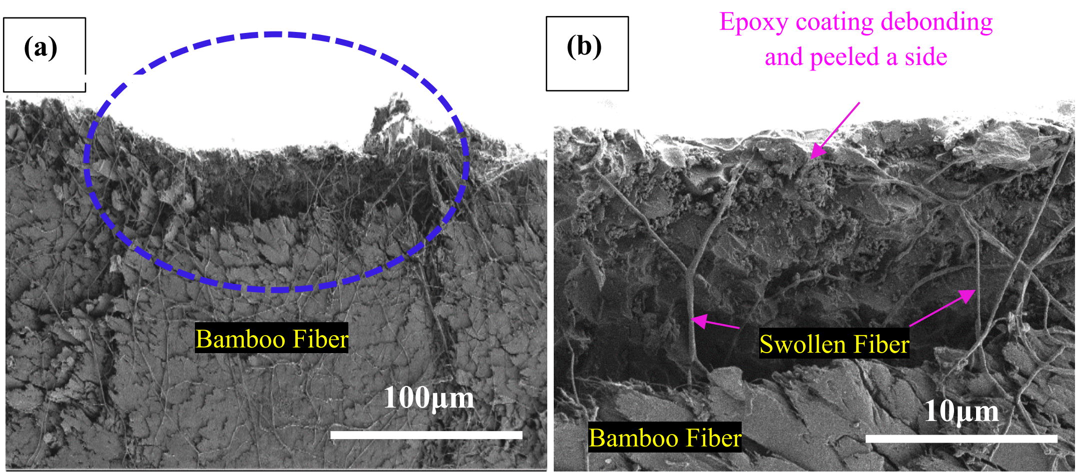


**Figure 10:** Cross-sectional micrograph of epoxy coated bamboo strips after immersing in SC0% (a) magnification 100x and (b) magnification 500x

## 4.CONCLUSION

The study provides significant insights into the morphological properties of epoxy-coated bamboo fibers after immersed in varied seawater concentration. The findings underscore the effectiveness of double epoxy coatings in enhancing the surface coverage and uniformity of bamboo strips. However, the research also reveals that while these double coatings offer some degree of protection to the bamboo surface, their resilience is notably compromised under high salinity conditions, as evidenced by the severe degradation. Strips immersed in SC0% showed the most severe degradation, followed by those in SC100% and SC50% seawater concentrations. The analysis highlights critical changes in the coating's integrity, including surface degradation and coating debonding, which are exacerbated by increased salinity levels. This deterioration suggests that while epoxy coatings can improve bamboo's resistance to marine environments, their protective capabilities may be limited to short-term applications. The insights gained from this work contribute to a broader understanding of how to optimize bamboo as a sustainable building material in coastal and marine applications.

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**Author contributions**

All authors contributed toward data analysis, drafting and critically revising the paper and agreed to be accountable for all aspects of the work.

**Disclosure of conflict of interest**

The authors have no disclosures to declare.

**Compliance with ethical standards**

The work is compliant with ethical standards.

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