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Review Article

Enhancing durability and sustainability of marine structures using FRP-reinforced seawater sea-sand concrete: A review

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ABSTRACT
By 2024, it is expected that there will be more people on the planet than 8.2 billion, which would increase need for infrastructure development. As a result, there are now more people using cement, especially in nations like India, which is concerning for the environment. As a result, in areas where freshwater resources are few, saltwater sea-sand concrete (SWSSC) has become a viable option for building. The durability and safety of structures are jeopardized by the use of traditional steel reinforcement in SWSSC, which increases the danger of corrosion in maritime conditions. Because of their improved mechanical qualities and resistance to corrosion, fiber-reinforced polymer (FRP) bars—more especially, glass fiber-reinforced polymer, or GFRP—have the potential to be a practical substitute for steel in SWSSC. The bond strength, tensile strength, and flexural strength of FRP bars in SWSSC in maritime conditions are highlighted in the study. According to experimental findings, FRP-reinforced SWSSC outperforms steel-reinforced counterparts in terms of structural longevity, increased load-bearing capability, and significantly lower maintenance costs. Furthermore, following extended exposure to saltwater, FRP bars maintain 85–90% of their initial tensile and flexural capabilities. By lowering dependency on freshwater and river sand, the use of FRP bars in SWSSC not only tackles corrosion difficulties but also encourages sustainable construction. The potential of fiber-reinforced SWSSC as a robust, long-lasting, and ecologically friendly solution for maritime and coastal infrastructure is highlighted in this work, setting the stage for further study and useful implementations in the building sector.

1. Introduction

The need for infrastructure development to support urbanization and economic growth is growing as the world's population continues to climb, projected to reach over 8.2 billion in 2024 [1], [2]. Cement output has increased dramatically as a result, especially in nations like China, India, Vietnam, and the United States [3], with India ranking as the world's second-largest producer of cement [4].

Due to the country's growing urbanization and infrastructural development, India also consumes a huge amount of cement [5], which raises environmental issues and carbon emissions [4]. In the face of these difficulties, concrete building durability—particularly in corrosive environments—has emerged as a crucial concern.

Corrosion poses a significant threat to the durability and safety of reinforced concrete structures, particularly in coastal and marine environments. Conventional steel reinforcement is highly susceptible to corrosion when exposed to oxygen, moisture, and chloride ions. This susceptibility leads to deterioration of structural integrity, increased maintenance costs, and a reduction in the service life of structures [6]. Sea Water Sea-Sand Concrete (SWSSC) has emerged as a viable solution to these challenges, especially in regions with limited freshwater resources and abundant sea sand and saltwater [7]. SWSSC can help reduce the demand for freshwater and river sand in concrete production, promoting sustainability in the construction industry. However, using steel reinforcement in SWSSC can still result in corrosion issues due to the aggressive marine environment [8].

Fiber-Reinforced Polymer (FRP) bars have gained attention as a potential solution to the corrosion problem in SWSSC. Due to their excellent corrosion resistance, composite bars such as Basalt Fiber Reinforced Polymer (BFRP) and Glass Fiber Reinforced Polymer (GFRP) are well-suited for use in harsh marine environments [9]. Studies have shown that composite bars offer superior mechanical and bond strength compared to conventional steel bars, as well as enhanced durability for concrete structures. The incorporation of FRP bars with SWSSC may lead to the development of long-lasting and environmentally friendly concrete constructions, thereby reducing the overall environmental impact of construction projects [10].

This research emphasizes the use of various composite bars, particularly FRP bars, in Sea Water Sea-Sand Concrete (SWSSC), focusing on bond behavior, corrosion resistance, and structural performance. It also explores the potential of SWSSC with composite reinforcement as a sustainable alternative to traditional steel reinforcement in future applications.

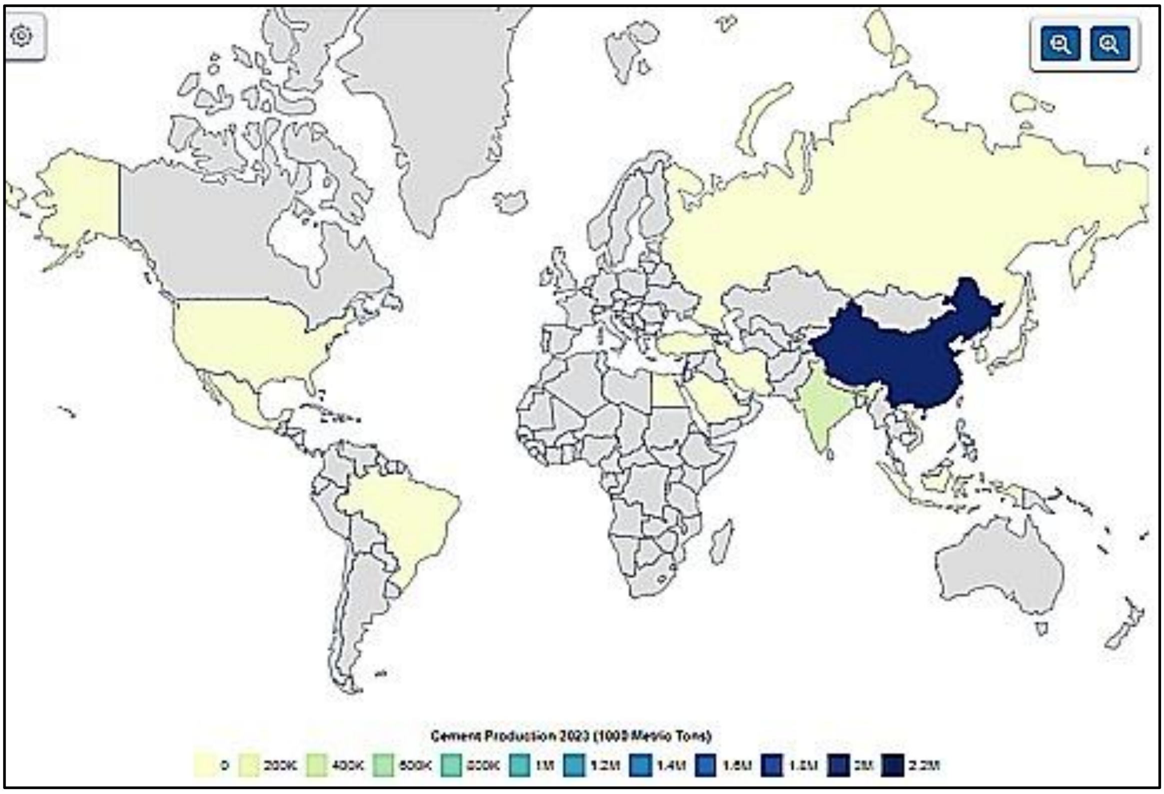


Figure 1: Concrete production.

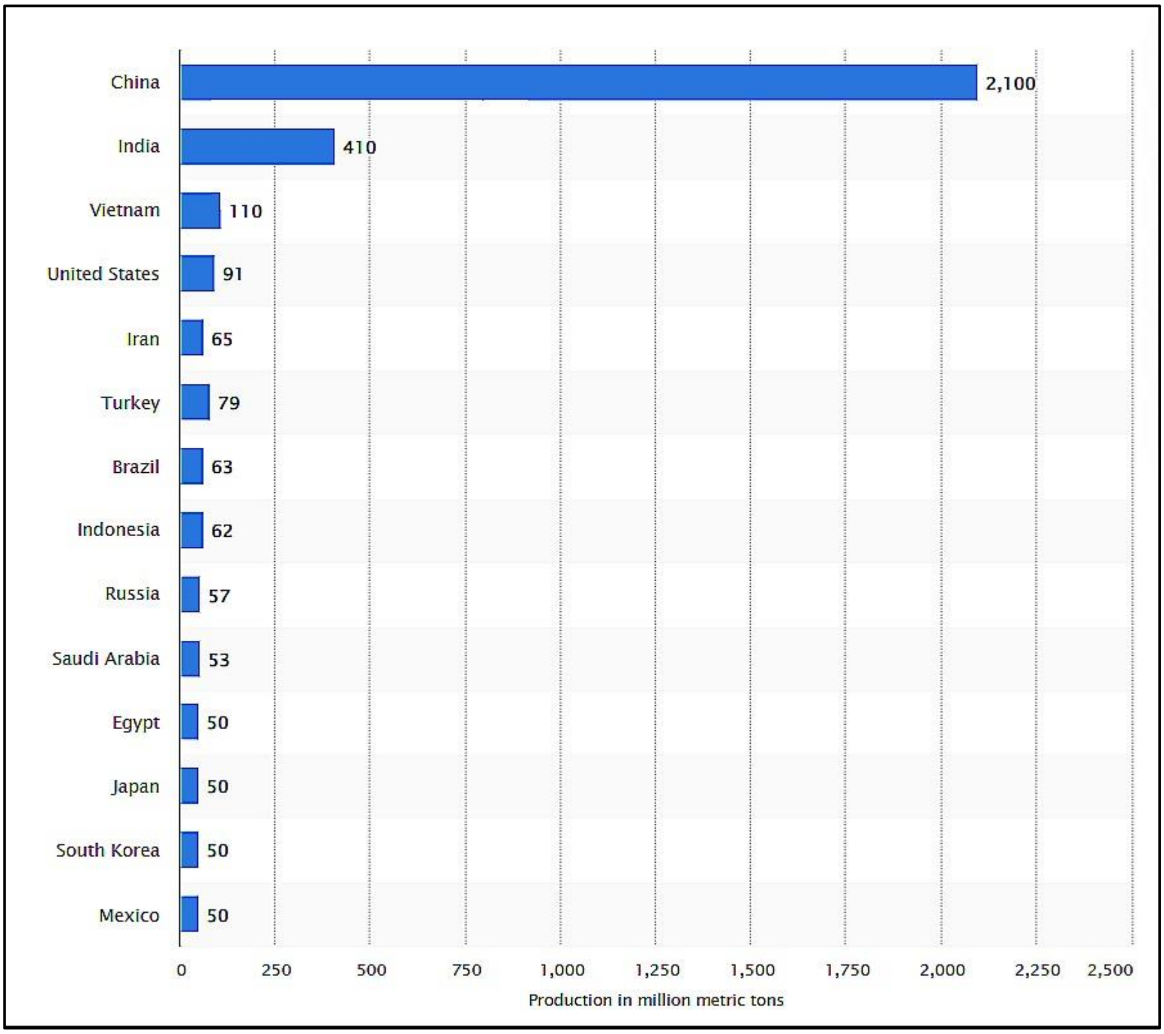


Figure 2: Top concrete producing countries.

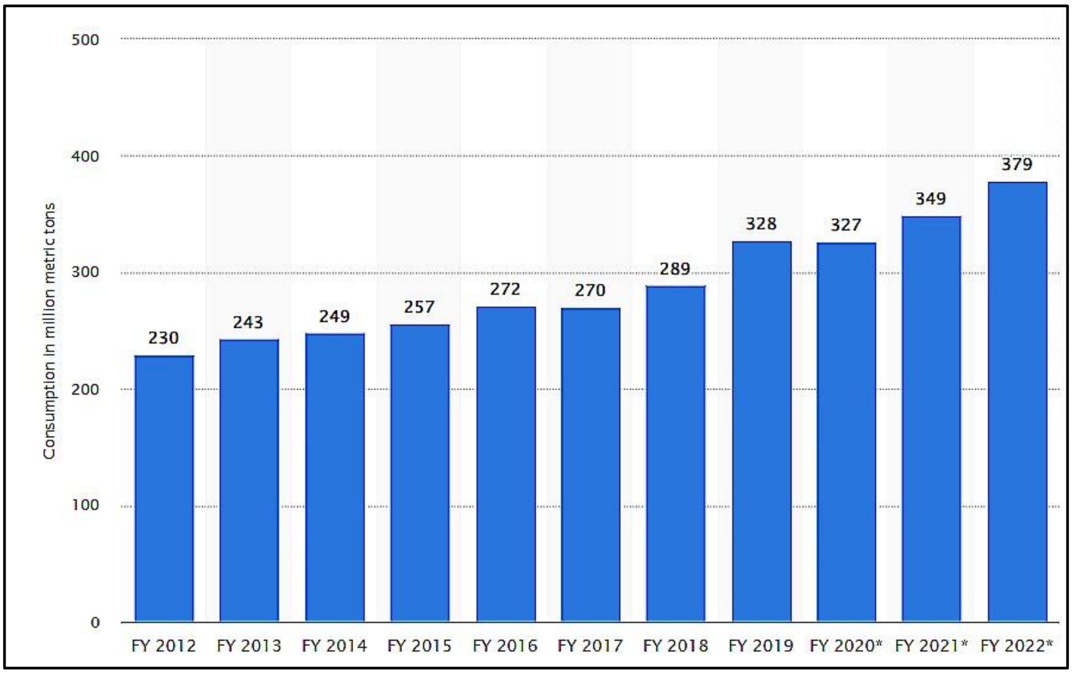


Figure 3: Consumption of cement in India.

2. Characteristics of the raw materials

2.1 Sea sand

The origin of sea sands can have a substantial impact on their physical and chemical characteristics. Sea sands are mostly found in coastal, marine, and island environments. These sea sands need to have their performance carefully monitored and managed before they can be utilized as fine aggregate in concrete. Tests for sea sand that are required include sieve analysis, loss on ignition (LOI) because to shell content, specific gravity, bulk density, apparent density, and chloride concentration. Among them, sieve analysis tests should be used to assess the fineness modulus and grading of fine aggregates, which are important physical parameters that impact the performance of concrete. The necessary standards that apply to the building site, such as the JTG E42-2005 Chinese code, AS1141.11.1-2009 Australian code, and IS460-1962 Indian Standard Code (Revised), should be followed when conducting the sieve tests and ASTM C136.

Particularly in areas where sand is expensive and scarce, sea sand is being considered as a feasible substitute for river sand in concrete building [11] Although worries about the high chloride concentration in sea sand offer serious problems to structural integrity and durability, its usage can assist mitigate the environmental effect associated with excessive river sand mining [12]. Research has demonstrated that sea sand can have strength characteristics that are on par with or even better than river sand when treated appropriately to lower the salt content, which makes it a good material for building [13]. Sea sand has the potential to be a sustainable solution for the building industry, as evidenced by the continuous study into its qualities and the development of techniques to improve its usage in concrete mixes.

2.2 Sea water

The use of seawater in concrete building has gained attention as a viable resource, especially in areas where freshwater is scarce. This practice can lessen dependency on conventional water supplies [12]. Although the high amounts of chlorides in seawater can cause corrosion in steel reinforcement, which can negatively impact concrete's longevity, scientists are working to reduce these impacts and improve the performance of saltwater-mixed concrete [13]. According to studies, seawater may improve the mechanical qualities of concrete when combined with appropriately treated sea sand, which makes it a feasible alternative for building in coastal [11]. In order to create more sustainable building practices, ongoing research attempts to gain a better understanding of the long-term effects of incorporating saltwater into concrete formulas.

2.3 Seawater sea sand concrete (SWSSC)

Slump values are often used to evaluate the workability of fresh seawater sea-sand concrete (SWSSC), in accordance with ASTM C-143 and IS 1199-1959 criteria. According to earlier research, adding sea sand and seawater to the concrete mix may make it less workable [14]. Mortars made with seawater and sea sand have also been found to exhibit significant strength loss at early ages [15]. Experimental results show that adding saltwater to the mixture improves the concrete's cohesiveness and viscosity when compared to regular concrete created with tap water. Moreover, research indicates that the general workability of SWSSC is relatively unaffected by the presence of contaminants like coal or clay in the sea sand. After examination, it was discovered that, with the right mix composition, saltwater sea-sand concrete (SWSSC) could achieve workability and long-term compressive strengths that were on par with ordinary concrete. Furthermore, it has been demonstrated that adding sea sand and saltwater to alkali-activated slag concrete improves it; mixtures of the two materials show the highest shear fracture energy and improved bond strength [12].

2.4 Manufacturing of composite bars

Fiber-reinforced polymer (FRP) bars are manufactured using various methods, each tailored to achieve specific properties and applications. Pultrusion is a common technique where continuous strands of fiber are pulled through a resin bath and cured in a heated die, resulting in strong, consistent profiles. Filament winding allows for complex shapes by winding saturated fibers around a mandrel, while resin transfer molding (RTM) involves injecting resin into a fiber-filled mold under pressure for enhanced mechanical properties. Compression molding is suitable for bulk parts, whereas hand lay-up and spray-up methods offer flexibility for custom shapes and larger components, respectively. Vacuum infusion promotes low void content and high-quality finishes, and 3D printing enables innovative designs through additive manufacturing techniques. The choice of method ultimately depends on the specific requirements of the application, including desired strength, geometry, and production volume.

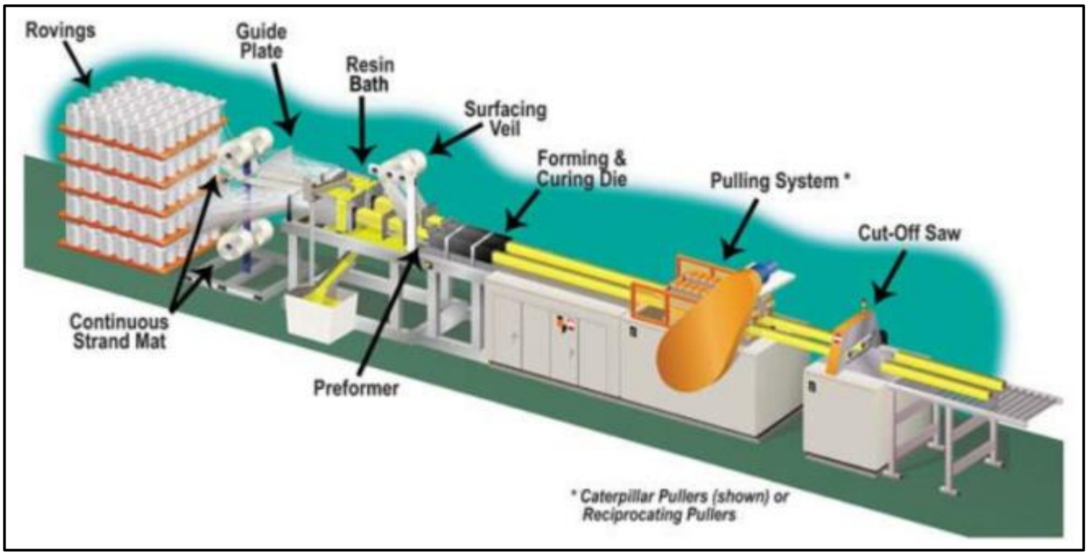


Figure 4: Manufacturing process (Pultrusion).

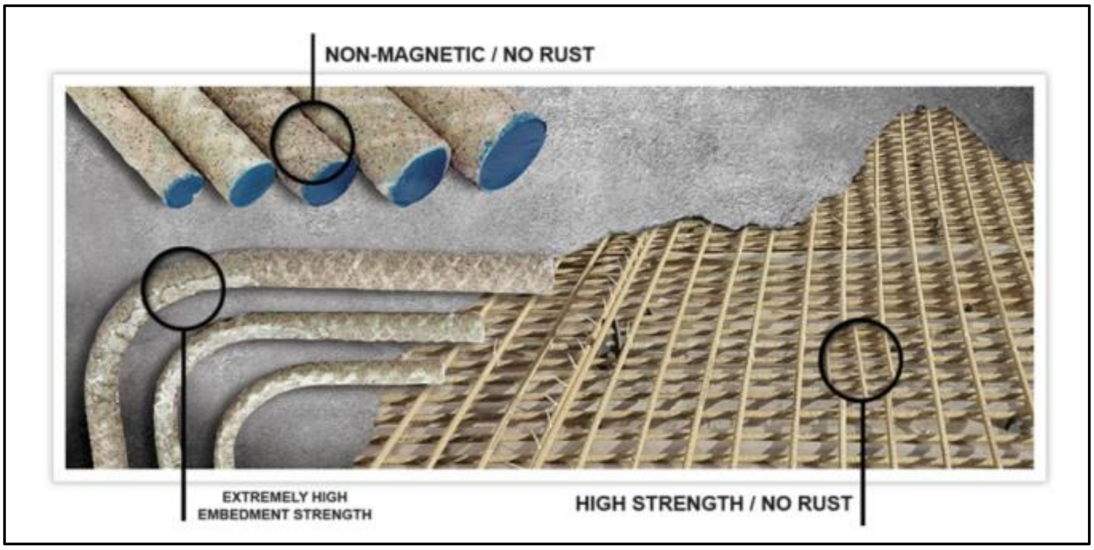


Figure 5: Glass fiber polymer reinforcement.

According to pultrusion is a process that involves drawing continuous fibers through a resin bath and filament winding, enabling precise control over fiber orientation. The type and quantity of reinforcing fibers, as well as their orientation within the matrix, significantly influence the characteristics of FRP bars. These bars offer several advantages over traditional steel reinforcement, including higher strength-to-weight ratios, superior fatigue resistance, and improved corrosion resistance. These qualities enhance the durability and lifespan of reinforced concrete structures while reducing maintenance costs [16]. Additionally, the low thermal and electrical conductivity of FRP materials further supports their use in sustainable construction practices, particularly in environments sensitive to electromagnetic interference.

3. Effect of GFRP reinforcement in SWSSC

Bond strength, tensile strength, flexural strength, and long-term performance are all critical parameters for evaluating fiber-reinforced polymer (FRP) bars in seawater sea-sand concrete (SWSSC), particularly for their application in marine environments.

3.1 Bond strength

Because FRP is more corrosion resistant than steel reinforcement, the bond strength between FRP bars and SWSSC has significantly improved. According to research, bond strength in SWSSC is increased by 15-20% when compared to regular concrete, and it deteriorates less in marine environments when geopolymers are used [17]. There was a 20% increase in the bond strength of glass fiber-reinforced polymer (GFRP) bars when exposed to the environment, in addition to a decrease in bond-slip [18]. Furthermore, compared to ordinary SWSSC, GFRP-reinforced ultra-high strength concrete demonstrated a 25% improvement in bond strength, reaching 18 MPa [19].

Below graph presents data derived from CSA-S6-14. The black line indicates the estimated values specified in the code, while the red line represents the experimentally calculated values [17].

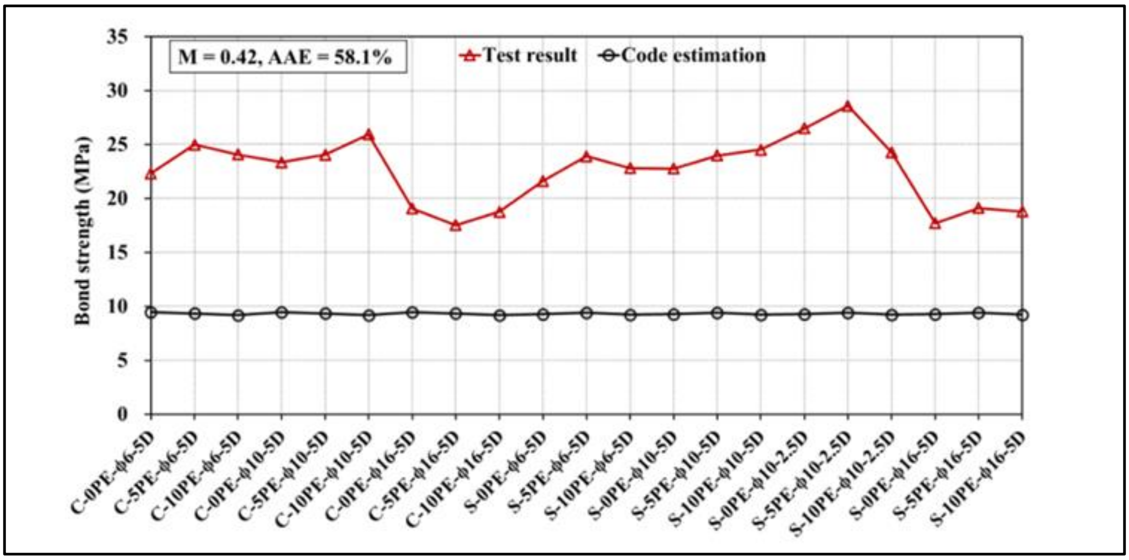


Figure 6: Bond strength graph.

3.2 Tensile strength

The long-term performance of FRP bars in SWSSC is largely dependent on their tensile strength, especially in harsh maritime conditions. Research has demonstrated that even after extended exposure to saltwater, GFRP bars maintain more than 90% of their initial tensile strength [20]. After 18 months, GFRP bars maintained 90% of their tensile strength during continuous loading and chloride exposure [21]. After two years in saltwater, GFRP bars retained 85% of their tensile strength, according to another study, which makes them ideal for marine applications.

The graph displays tensile strength retention percentages for various materials subjected to environmental exposure over different durations (1, 6, 12, and 24 months). The reference material (REF) maintains the highest retention, while tensile strength declines more significantly over time for materials exposed to seawater (SW) compared to freshwater (FC) [20].

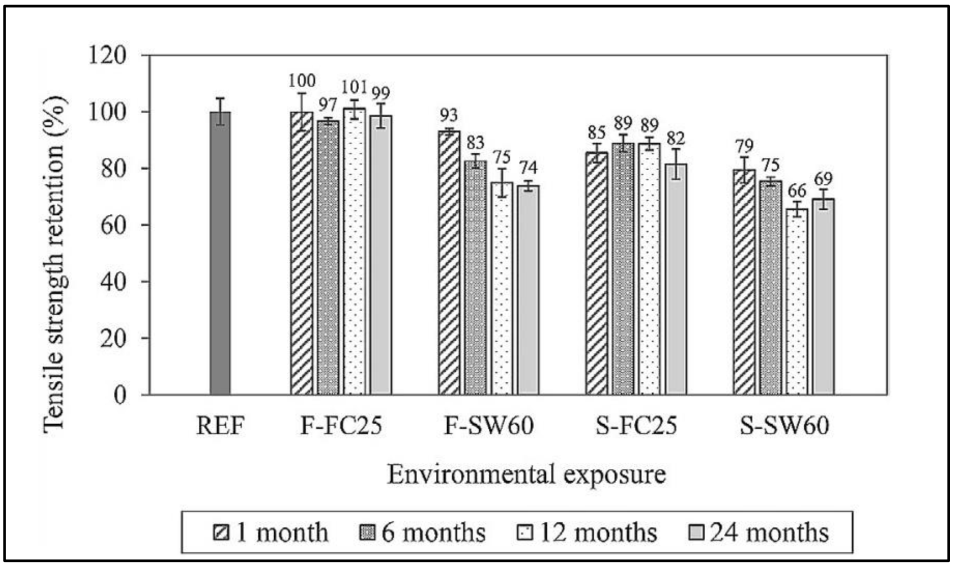
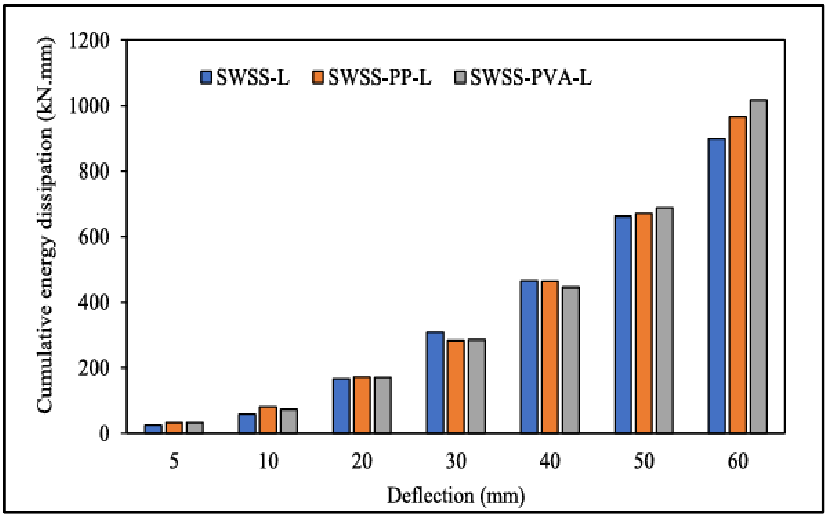


Figure 7: Tensile strength retention graph.

3.3 Flexural strength

Another crucial metric for assessing FRP bar performance in SWSSC is flexural strength. Studies have demonstrated that GFRP bars greatly increase the flexural strength of SWSSC. When compared to traditional steel-reinforced slabs, GFRP-reinforced slabs showed a 25% improvement in load-bearing capacity and a 30% decrease in fracture width [22]. In comparable marine settings, concrete slabs reinforced with glass fiber polymer (GFRP) demonstrated a flexural strength that was 10-15% more than that of steel-reinforced slabs [23]. According to a different investigation, following 18 months of continuous loading and exposure to chloride, GFRP-reinforced beams maintained 90% of their flexural capacity [24].

The graphs illustrate the cumulative energy dissipation of different composite materials as a function of deflection. It is observed that for both high and low deflection ranges, the SWSS-PP composite consistently shows higher energy dissipation compared to the other variants [22].



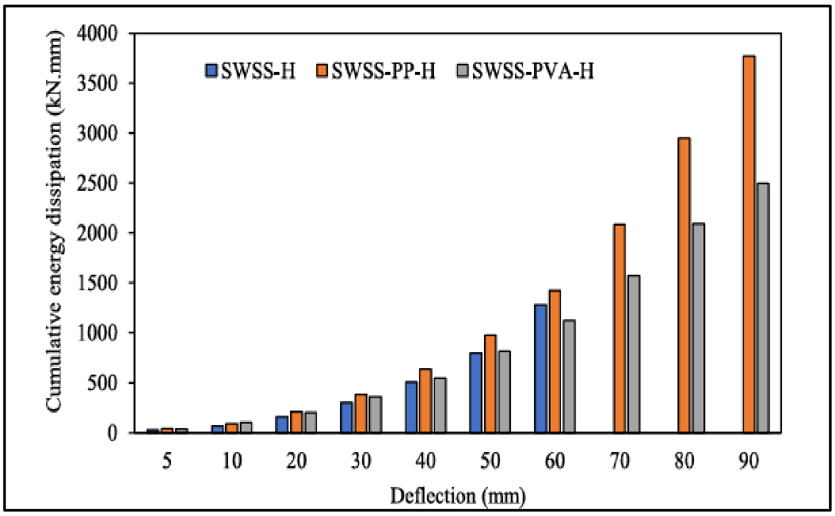


Figure 8: Cumulative energy dissipation vs. deflection graph.

3.4 Long-term performance

Many studies have been conducted on the long-term performance of FRP bars in SWSSC, especially in challenging maritime settings. Particularly GFRP bars have demonstrated exceptional resilience to sustained loads, extended exposure to saltwater, and chloride infiltration. While GFRP bars implanted in SWSSC kept 90% of their flexural strength after 18 months, GFRP-reinforced beams retained 85–90% of their initial flexural capacity after two years of exposure [6, 21]. After two years in saltwater, GFRP bars likewise held onto 85% of their tensile strength. Additionally, after a year in a marine environment, GFRP bars showed no corrosion, whereas steel bars had noticeable surface corrosion [1]. These findings collectively emphasize the long-term durability and performance of FRP-reinforced SWSSC in marine structures. Together, these results highlight the FRP-reinforced SWSSC's long-term performance and endurance in maritime constructions.

4. Conclusions

The findings from this research strongly support the use of Fiber-Reinforced Polymer (FRP) bars, particularly GFRP as effective alternatives to traditional steel reinforcement in Seawater Sea-Sand Concrete (SWSSC). FRP bars in SWSSC offer enhanced durability, superior mechanical properties, and sustainability, making them ideal for long-term coastal infrastructure.

The key advantages of FRP bars include:

- FRP-reinforced SWSSC exhibits a 15-25% increase in bond strength over regular concrete, enhancing structural performance.
- GFRP bars maintain 85-90% of their tensile and flexural strength after two years in saltwater exposure, indicating durability.

GFRP bars show superior long-term corrosion resistance compared to steel, making them ideal for marine environments.

Authors' contributions

The author read and approved the final manuscript.

Conflicts of interest

The author declares no conflict of interest.

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Data availability

No new data were created.

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