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PERFORMANCE EVALUATION OF FIBER-REINFORCED CONCRETE USING SEAWATER CURING AND PARTIAL SEA SAND REPLACEMENT

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Abstract

The growing loss of fresh water and river sands used as aggregate materials for concrete is an increasing environmental problem, especially in coastal areas that have abundant unexploited marine resources. Though several earlier studies have evaluated seawater concrete, replacing river sands with sea sand, and fiber reinforced concrete, very little previous research has evaluated the combined impact of seawater curing, partial replacement of river sand with sea sand, and the addition of glass, steel and carbon fibers to evaluate the overall performance of fiber reinforced concrete made with seawater curing and 20 percent replacement of river sand with sea sand, at a constant fiber content (volume fraction) of 1%, and a target compressive strength of 40 MPa. Eight concrete mixtures were tested for compressive strength (strength when under a compression force), tensile strength (strength when under a tensile or pulling force), flexural strength (strength when bending) and impact energy after post-construction water absorption and ultrasonic pulse velocity at 28 days of curing in both freshwater and simulated sea water environments. Results show that marine cured materials reduced the compressive strength of plain concrete by about 7.6%, as well as adversely affected other mechanical and durability properties; however, fiber reinforcement substantially minimized these negative effects. Steel fiber concrete was the most improved type of fiber concrete, enhancing the compressive strength by up to 16.5%, as well as enhancing the post-crack impact energy more than six times over the control mixture. Carbon fiber reinforced concrete demonstrated superior durability characteristics, Water absorption increased from 3.80% in freshwater-cured plain concrete to 4.25% in marine-cured plain concrete, while fiber-reinforced concrete under marine conditions reduced the value to as low as 3.40% Similarly, ultrasonic pulse velocity decreased from 3.80 km/s to 3.68 km/s in marine plain concrete, whereas fiber-reinforced mixes, particularly steel fiber concrete, achieved values up to 4.11 km/s, indicating improved internal quality. Glass fibers provided moderate improvements in both strength and durability properties, and overall, fiber reinforcement reduced permeability and enhanced crack resistance under marine exposure conditions. These results demonstrated the potential of using seawater to cure fiber-reinforced concrete and *using sea sand to replace part of the fine aggregate to provide durable performance and thus support its potential as a viable alternative to traditional materials in coastal areas or where access to resources is limited.*

1. INTRODUCTION

The majority of modern infrastructure continues to be constructed with concrete because of its ability to provide a reliable mechanical performance at an affordable price and under various environmental conditions [1]. However, the production of concrete is also dependent on the use of large quantities of water and river sand which have become increasingly scarce. The increased rate of urbanization has led to an increase in river sand extraction, and this has resulted in several negative effects including the degradation of ecosystems, the loss of balance of ground water, and the erosion of river banks [2] , [3]. This highlights the urgent need to identify alternative materials since it is estimated that there will be over 60 billion tons of sand and gravel used per year globally by 2030 [4]. Water scarcity is another major issue as over 40% of the world's population experience water stress today and this will increase as cities grow and as weather changes [5], [6]. This has caused much concern about alternative water source that can be used to support concrete production so that we do not rely as heavily on our current fresh water supplies [7], [8].

Coastal and island areas are potential locations where natural resources may be substituted by using sea sand and seawater. Using partial replacement of river sand with sea sand and replacing freshwater with seawater is a method to lower the environmental footprint of producing concrete while increasing local availability of raw materials (self-sufficiency) within coastal marine environments [9],[10]. Prior research has shown that when properly processed, the mechanical performance of both treated sea sand and seawater can be equivalent to that of traditional concrete provided that the environment is tightly controlled [9]. The presence of chloride and sulfate in marine materials causes concern regarding the long-term durability of such concrete, particularly concerning matrix degradation and corrosion of steel reinforcement [11].

The main issue is that SWSSC has to be durable without being structurally weak. The use of traditional steel reinforcements is limited by chloride-induced corrosion, leading to an increased focus on alternative materials with corrosion resistant properties; such as discrete fibers [10], [11] which can provide both strength in tension and ability to control cracks, absorb energy and resist impact, along with reduced crack width and therefore less opportunity for corrosive ions to enter the structure from the marine environment.

Although there is a considerable amount of research that has explored individual aspects of seawater mixed concrete (SWMC), sea sand replacement (SSR) and fiber reinforced concrete (FRC); as well as the potential interactions among these variables when they are used together, very little work has assessed the synergistic effects of SWMC/SSR/FRC on hydration behavior, pore structure and mechanical properties. There is also a significant lack of comprehensive comparative assessments of FRC using glass, steel and carbon fibers at a constant volume fraction when cured under either freshwater or marine conditions.

Therefore, the purpose of this research is to investigate the mechanical and durability related performance of SWMC with SSR and containing glass, steel and carbon fibers and to evaluate each type of fiber in order to determine the most suitable for use in coastal regions where access to freshwater is limited and resources are scarce; therefore to ultimately determine if it is feasible to develop marine based concrete systems for use in structural applications in such regions [5] [10].

2. Literature Review:

2.1 Environmental Pressures on Conventional Concrete Materials

The production of traditional concrete has become associated with a range of environmental degradations as a result of the removal of large amounts of river sand for use in construction processes. This unsustainable process of removing sand from rivers has led to a number of negative impacts including erosion of river banks, loss of ecosystems and disruption to normal sediment transport patterns [2][3] . With the majority of sand and gravel being consumed by the construction industry globally (therefore they are among the most heavily extracted solid resources) it would be reasonable to assume that continued reliance upon river sand as opposed to finding suitable alternatives will continue to place additional ecological pressure [9].

Water scarcity for fresh water further complicates these problems. Over 40 percent of the world's population is experiencing water stress today, and there are increasing predictions that it will get worse because of both urban growth and climate variability [5] [6]. The use of industrial freshwater by concrete production has prompted a need to find alternative water sources that can reduce our dependence on existing freshwater reserves [7][8].

2.2 Seawater and Sea Sand as Concrete Constituents

The study of the use of seawater and sea sand (also known as beach sand) as an alternative source for producing concrete has also been examined as possible alternatives for coastal and island communities. Studies have shown that provided appropriate treatment or processing of both materials and their mixing ratios; the mechanical properties of the resulting marine concretes can be equivalent to those of traditional concrete at typical strength levels. The experimental results confirm that, by controlling the level of chlorides in the mixtures, it may be possible to replace up to half of river sand used in concretes with sea sand without significantly compromising either the compressive or tensile strengths of the resulting concretes [12].

Although previous research indicates that marine materials can provide several benefits for the development of durable marine concretes, there are still many concerns regarding the long term durability of these materials. For example, the presence of chloride and sulphate ions in marine materials can influence the hydration reactions and may lead to potential problems related to long term degradation of the concretes unless adequate measures are taken to manage this problem. Therefore, consideration should be given to selecting suitable reinforcing materials and designing mixes with durability in mind when developing marine based concrete systems [6], [9].

2.3 Fiber Reinforcement in Marine Exposure Conditions

Fiber reinforcement is being used increasingly to improve tensile properties (tensile strength), crack resistance (crack control), toughness, and post-cracking performance of concrete. In addition, discrete fibers help in transferring stresses across cracks in concrete and limit crack propagation and chloride migration in marine environments [11].

Glass fibers are said to improve tensile performance and crack resistance in seawater and sea sand concretes at moderate dosages [13] and steel fibers significantly increase both strength and ductility and also increase impact resistance. However, corrosion can affect long-term performance of steel fibers in chloride rich environments. On the other hand, carbon fibers have been identified as a corrosion resistant option with very high tensile strengths, excellent crack control, and stable mechanical performance under extreme exposure conditions [11]. The differences among these fiber options clearly illustrate the need for an objective comparison of different fiber types for use in marine-based concrete applications.

2.4 Limitations of Existing Studies and Identified Research Gap

Although there is a significant body of literature addressing each of these three individual concepts (seawater-mixed concrete, sea sand replacement and fiber reinforced), relatively little research has been conducted to evaluate all three in combination at the same time and with consistent testing methodologies. Therefore, the majority of existing studies either utilize fresh water for curing of fiber reinforced concrete or examine the effects of seawater and sea sand on concrete without the use of fibers [9],[12]. As such, the interaction of various fiber types and marine environmental components to affect both mechanical properties and long-term durability are still poorly understood.

In addition to this, most research investigations have focused on one particular type of fiber or have investigated marine-based concrete systems as being made up of different mix proportions and curing methods. Therefore, it is difficult to compare directly how effective glass, steel and carbon fibers are at reducing performance loss from curing in seawater and replacing part of the aggregate (sand) with sea sand. Furthermore, differences in the mix design parameters, test conditions (e.g., curing), and test results/indicators (i.e., performance indicators) among all of the previously reported research studies severely restricts their ability to be generalized. The above-mentioned research study issues clearly indicate the need for controlled comparative research studies investigating multiple types of fibers within concrete made by using seawater curing and replacing part of the fine aggregate with sea sand in order to compare directly how effective each type of fiber is at reducing performance loss from curing in seawater and replacing part of the fine aggregate with sea sand. Therefore, to directly evaluate effectiveness of fibers of different types controlled comparative research is needed [14].

3. Materials & Methodology

3.1 Materials

The materials used in this study included ordinary Portland cement, fine and coarse aggregates, sea sand, freshwater and simulated seawater, reproducibility of results.

3.1.1 Cement

The Type I, Grade 53 Ordinary Portland Cement was utilized as a binder in this research project to obtain an average compressive strength of 40 MPa. It also met the ASTM C150 [15] standards of performance and was selected for consistency of strength development. The physical and chemical properties of cement used in this study are presented in Table 1.

Table 1: physical and chemical properties of cement

Chemical Properties						
Lime Saturation Factor	Alumina Iron Ratio	Insoluble Residue	Magnesia	Sulphuric Anhydride	Total Chlorides	Ignition Loss
0.66-1.02	NR	1.5%max	4%max	3%max	NR	3%max
Physical Properties						
Specific gravity	Consistency (%)	Initial Setting Time (min)	Final Setting Time (min)	Soundness (%)	28-Days Compressive Strength (MPa)	
3.15	28.5	102	203	0.10	49.61	

3.1.2 Fine Aggregates

Lawrencepur river sand is used as the reference fine aggregate that passed through the 4.75 mm sieve size, the gradation analysis of fine aggregates (sand) is illustrated in Figure 1. Both gradations of both sands and their physical properties given in Table 2 are in compliance with the ASTM C33 [16] limits.

Table 2: Physical Properties of Lawrencepur Sand

Property	Value
Specific gravity	2.65-2.75
Fineness modulus	2.2-2.6
Bulk density (SSD)	1550-1650 kg/m^3
Water absorption	3-4%
Moisture content	0.5-1%
Shape	Angular
Color	Grey
Radioactivity	Low

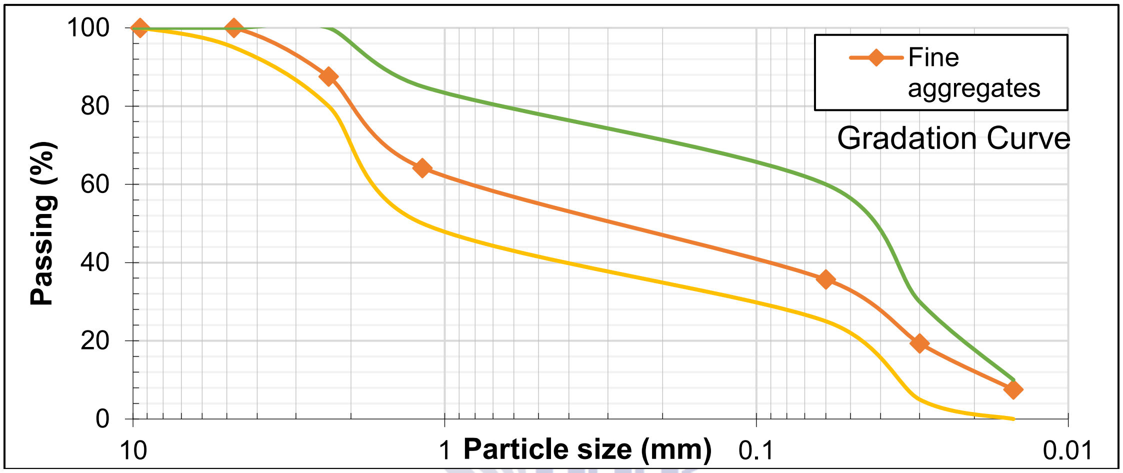

Figure 1: Gradation Analysis of Fine Aggregates of Sand

3.1.3 Sea Sand

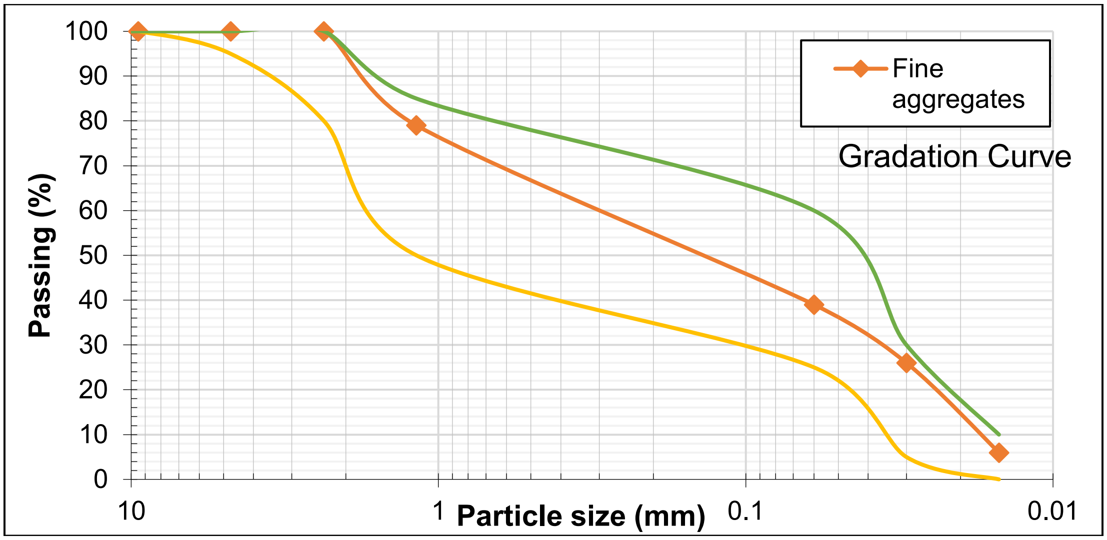

Figure 2: Gradation Analysis of Fine Aggregates of Sea Sand

The sea sand that was taken from the Karachi coast has been utilized to replace 20% of the river sand in marine mixtures to demonstrate the use of readily available local materials on the coast to produce cement. The gradation curve of sea sand is shown in Figure 2.

3.1.4 Coarse Aggregates

Crushed Sargodha Stone with a nominal max size of 12.5mm has been used as coarse aggregate the gradation analysis of coarse aggregates is presented in Figure 3. The Aggregates are well graded and the physical and mechanical properties of coarse aggregates given in Table 3 meet the ASTM C33 [16].

Table 3: Physical and Mechanical Properties of Coarse Aggregates

Property	Value
Specific gravity	2.72
Bulk density	1533 kg/m^3
Water absorption	1.00%
Crushing value	17.90%
Impact value	11.60%
Voids	42.80%

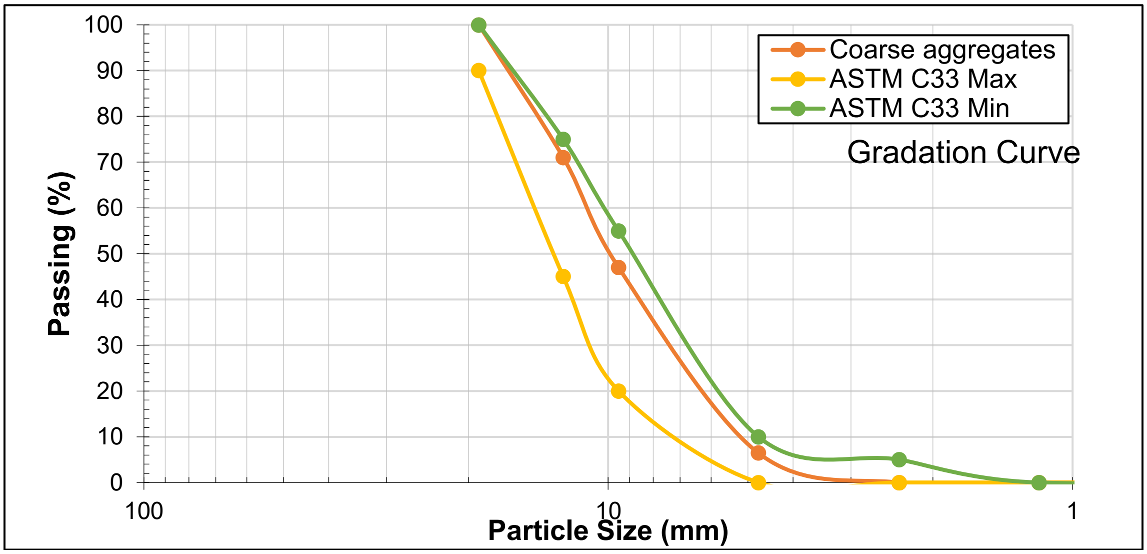

Figure 3: Gradation Analysis of Coarse Aggregates of Sand

3.1.5 Fresh Water

Potable water meeting the ASTM C1602 [17] standards has been used for the mixing and curing of control concrete specimen. Potable water meeting the ASTM C1602 [17] standards has also been used for the control mix.

3.1.6 Mixing Water and Seawater Simulation

A simulated seawater with 3.5% salinity was made by using Sodium Chloride (NaCl) and Magnesium Sulphate (MgSO4), and used for the mixing and curing of the marine specimens.

3.1.7 Fibers

Steel, glass, and carbon fibers were added as 1% by volume to designated mixes for evaluation of their performance in both fresh water and sea environments. The physical and mechanical properties of glass, steel, and carbon fibers are presented in Table 4

Table 4: Physical and Mechanical Properties of Glass, Steel and Carbon Fibers

Material	Property	Value
Glass Fiber	Density	2.55 – 2.6 g/cm³
	Tensile strength	1950 – 2050 MPa
	Young's modulus	72 – 85 GPa
	Compressive strength	4000 – 5000 MPa
	Shear modulus	30 – 36 GPa
	Elongation at break	3%
	Specific heat capacity	800 – 805 J/kg·K
	Chemical resistance	Good
Steel Fiber	Density	7850 kg/m³
	Tensile strength	500 – 1000 MPa
	Yield strength	250 – 500 MPa
	Elongation	10 – 30%
	Aspect ratio	20 – 100
	Diameter	0.2 – 1.0 mm
	Length	10 – 100 mm
	Cost	$0.5 – 1.0 /kg
Carbon Fiber	Density	1.7 – 2.2 g/cm³
	Tensile strength	3 – 7 GPa
	Young's modulus	200 – 500 GPa
	Compressive strength	1 – 3 GPa
	Elongation at break	0.1 – 2%
	Thermal conductivity	150 – 250 W/m·K
	Electrical conductivity	10^{-6} – 10^{-4} S/m
	Chemical resistance	Excellent

3.1.8 Chemical Admixture

The addition of 0.5% by weight of cement, polycarboxylate-based superplasticizer was used, to maintain the workability and ensured uniformity of fiber distribution among all the mixtures.

3.2 Mix Design

The concrete mix was designed with a proportion of 1:1.3:1.7 and a water–cement ratio of 0.45 to achieve the target strength 40MPa and workability. Eight different concrete mixes were developed to study how both marine-based constituents and the addition of fibers into the mix affect the final product. Each combination within the experimental design consisted of two types of concretes: a plain and a fiber reinforced version; however, each type was produced using either river sand and water for curing or sea sand replacing part of the river sand and using seawater for curing. All mixes contained Ordinary Portland Cement (Type I, Grade 53 (Maple Leaf). All mixes with fibers had the same fiber volume fraction (1%) that is large enough for an effective crack control but small enough so the mix remains workable. The proportions for the reference mixtures included 600 kg/m³ cement; 1020 kg/m³ coarse aggregate and 270 liters/m³ of water for mixing. The reference mixtures included 780 kg/m³ of river sand, whereas the mixtures incorporating sea sand replaced 20% of the river sand with sea sand (which equated to 624 kg/m³ river sand and 156 kg/m³ sea sand). The number of fibers added to each mixture to keep the fiber volume fraction constant varied with fiber density. Thus, the glass, steel and carbon fibers were added in quantities of 26 kg/m³, 78.5 kg/m³ and 17.5 kg/m³, respectively. A superplasticizer dosage of 3 kg/m³ (or 0.5% of the weight of cement) was utilized uniformly in all mixtures.

3.3 Preparation of Simulated Seawater

A simulated seawater solution was created to simulate marine exposure conditions. The simulation included a total of 35 grams of sodium chloride and 5 grams of magnesium sulfate in one liter of fresh water, which produced an approximate salinity of 3.5% for all marine concrete specimens. The simulated seawater was then used to mix and cure all the marine concrete specimens.

3.4 Mixing, Casting and Curing Procedure

The mixing of fresh concrete was done with a drum mixer. In the first step coarse and fine aggregate are mixed together (dry-mix). Then the cement is added to the mix, and then fibers are slowly added to the dry-mix to ensure they are evenly dispersed through the entire mix so as to prevent "balling". Finally, water (freshwater or simulated seawater) and the superplasticizer are added to the mix and the mixer continues to operate until the mix reaches a consistent finish. The mix proportions and curing conditions of all concrete mixtures are detailed in Table 5.

The fresh concrete was poured into molds in three layers. Each layer was manually compacted using 25 tamping strokes. After all layers had been compacted, the final compaction was completed on a vibrating table for about 2 minutes. The samples were removed from the molds after 24 hours and the curing process took place for 28 days. The reference samples were cured in freshwater while the marine samples were cured in simulated seawater.

Table 5: Mix proportions and curing conditions of plain & fiber-reinforced concrete mixes

Mix	Mix Category	Sand	Curing	Fiber	Fiber (kg)	River Sand (kg)	Sea Sand (kg)	Aggregate (kg)	Water (L)
1	Plain	River	Fresh	–	0	780	0	1020	270
2	Plain	Sea (20%)	Sea	–	0	624	156	1020	270
3	Glass FRC	River	Fresh	Glass	26	780	0	1020	270
4	Glass FRC	Sea (20%)	Sea	Glass	26	624	156	1020	270
5	Steel FRC	River	Fresh	Steel	78.5	780	0	1020	270
6	Steel FRC	Sea (20%)	Sea	Steel	78.5	624	156	1020	270
7	Carbon FRC	River	Fresh	Carbon	17.5	780	0	1020	270
8	Carbon FRC	Sea (20%)	Sea	Carbon	17.5	624	156	1020	270

3.5 Experimental Program

The workability of fresh concrete was tested according to ASTM C143 [18] through use of the slump test. The fresh density of the mixtures was calculated from measurements of the weight of compacted fresh concrete contained within a fixed volume container.

Compressive strength of all samples was determined at 28 days on cylindrical sample specimens that had been 100 mm in diameter and 200 mm in height as per ASTM C39 [19]. Tensile splitting strength of all the mixtures was also determined on the identical cylindrical sample specimen as per ASTM C496 [20]. The flexural strength of the samples was determined by ASTM C1609 [21] using prismatic test pieces (100mm x 100mm x 500mm) under two point load. The ultrasonic pulse velocity tests were carried out to determine the quality of the concrete in accordance with ASTM C597 [22] by using cylindrical specimens.

Water absorption tests were carried out using 100mm cube specimen according to ASTM C1585 [23]. Impact resistance was assessed by determining the impact resistance of the sample using 150mm diameter and 65mm thick disc specimens as per ACI 544.2R [24] by dropping a 4.54kg hammer from a height of 457mm.

4. Results and Discussion

4.1 Fresh Properties

4.1.1 Slump

Figure 4 shows the measured slump values for all mixtures.

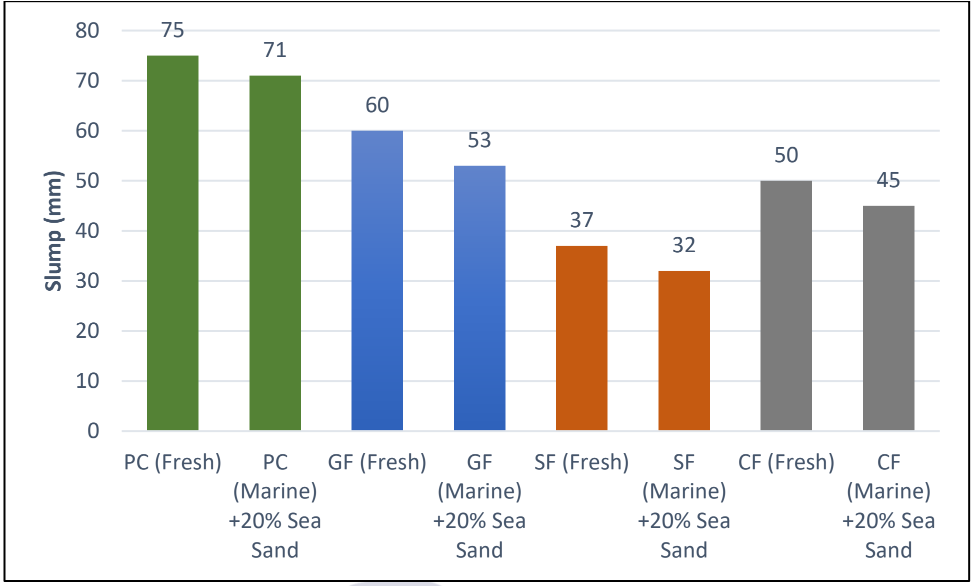

Figure 4: Slump Test Results

The control mix showed the highest slump value of 75 mm, while the marine mix decreased to 71 mm due to dissolved salts causing early stiffening and angular sea sand reducing lubrication. The addition of fibers further reduced slump, with glass fiber at 60 mm due to high surface area and water absorption, carbon fiber at 50 mm due to increased viscosity, and steel fiber showing the lowest value of 37 mm due to high stiffness and internal friction. Marine fiber mixes showed further reduction, with steel fiber reaching 32 mm. This is because fibers create a barrier that impedes the flow of cement paste and increase internal friction within the mix. Steel fibers also had the greatest impact on slump of the three types of fibers because of the greater modulus of elasticity and higher aspect ratio; while glass and carbon fibers had a lesser but still significant impact on slump. Additionally, marine mixtures always displayed less slump due to angular sea sand and increased rate of early hydration. Overall, the trend was: plain concrete > glass fiber > carbon fiber > steel fiber.

4.1.2 Fresh Density

The fresh density results are presented in Figure 5. The control mix showed 2385 kg/m³, while the marine mix decreased to 2376 kg/m³ due to lower specific gravity of sea sand, increased air content, and reduced packing efficiency. Steel fiber reinforced concrete showed the highest density of 2415 kg/m³ due to high specific gravity, followed by carbon fiber at 2395 kg/m³ due to better matrix filling, while glass fiber showed a slight decrease to 2378 kg/m³ due to internal voids and reduced flowability. This modest decrease is explained by the sea sand's finer particle size which raises the air content and decreases packing effectiveness. Steel fibers increase the mass per unit volume and produce denser concrete. Overall, the trend was: steel fiber > carbon fiber > plain concrete > glass fiber which indicates that fiber density has a larger effect on fresh concrete density than does marine constituents, and the smaller reduction observed in marine mixtures may be the result of changes in packing efficiency and mix rheology resulting from partial substitution of sea sand.

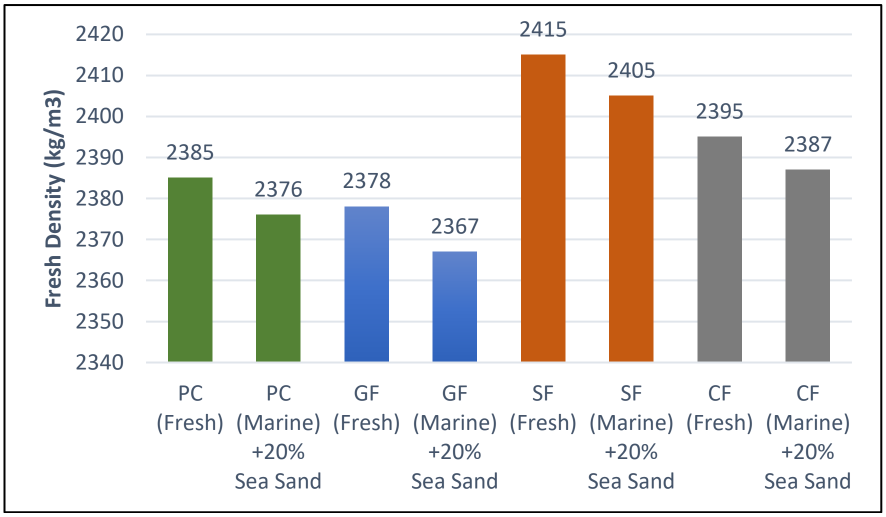

Figure 5: Fresh Density Results

4.1.3 Compressive Strength

The results from the 28day compressive strength tests clearly show that plain concrete cured in the marine environment has a lower compressive strength than the control mixture, where the control mix achieved 39.5 MPa and the marine m ix reduced to 36.5 MPa, indicating a 7.6% decline. This is consistent with previous research that indicates that certain materials found in the marine environment have an adverse effect on the formation of the matrix of concrete, chloride ions accelerate early hydration but contribute to long-term microstructural instability and increased porosity and sulphates may form expansive products such as ettringite, increasing porosity and micro cracking. In addition, Figure 6 illustrate the compressive strength values as well as the percent difference in strength for each type of composite under the two curing conditions. The test results demonstrate that fiber reinforcement was beneficial to increasing the compressive strength of composites cured under both environments, with glass fiber reaching 42.5 MPa, carbon fiber 43.5 MPa, and steel fiber showing the highest value of 46.0 MPa. Of all the types of fiber reinforcement tested, steel fiber reinforced composite had the greatest compressive strength, followed by Glass fiber reinforced composite, showing an overall trend of steel fiber > carbon fiber > glass fiber > plain concrete. The increase in strength is attributed to the capability of fibers to arrest cracks and redistribute stresses within the concrete matrix. Steel fibers proved to be the most effective as a result of their high stiffness and good mechanical fit to the cement paste; Carbon fibers showed good crack bridging characteristics, and Glass fibers resulted in a moderate increase in strength. All of the fiber-reinforced mixtures tested had higher strengths than the corresponding unreinforced mixtures and thus show that the inclusion of fibers will help to mitigate the effects of marine curing on compressive strength.

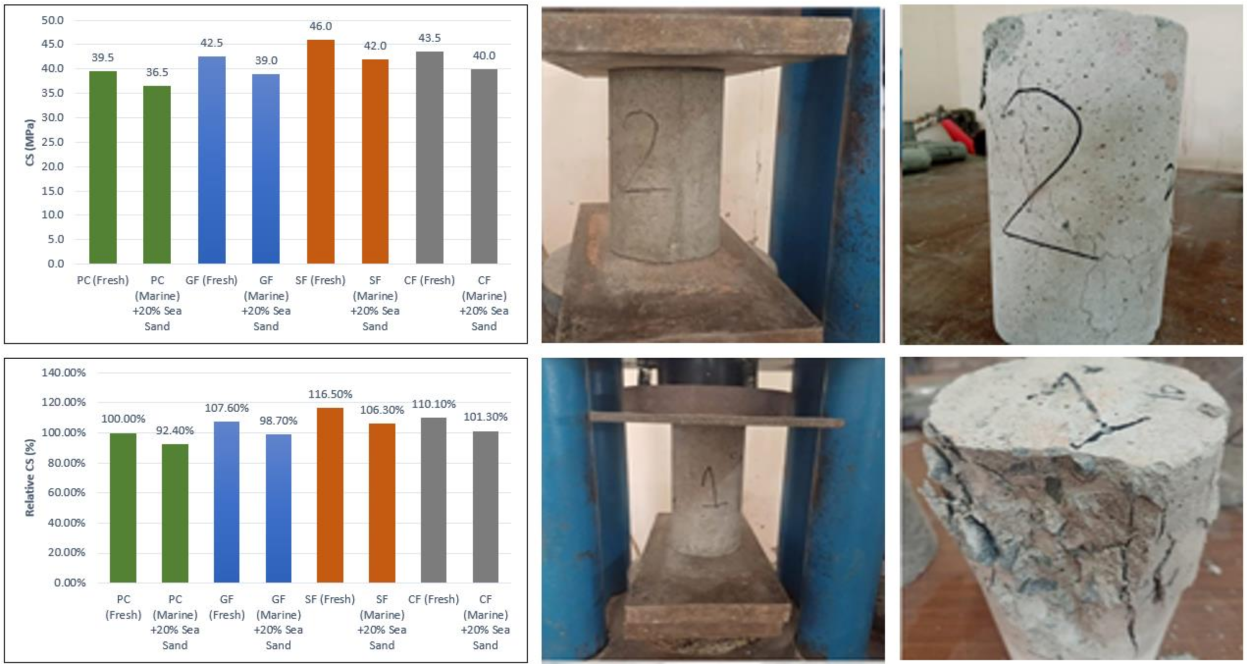

Figure 6: Compressive Strength Samples and Test Results

4.1.4 Splitting Tensile Strength

Plain concrete subjected to marine curing showed a lower tensile strength than the reference (control) mixture, where the control mix showed 3.53 MPa and the marine mix reduced to 3.38 MPa, or 4.2% lower than the control mix due to increased porosity and microcrack formation. This suggests that the marine cured plain concrete is more prone to develop microcracks when it is subjected to tensile forces than the control plain concrete. Relative percentages of tensile strengths for the different mixes are shown in Figure 7. Overall, all fiber reinforced concretes exhibit better tensile properties under both curing methods, with glass fiber reaching 4.02 MPa, carbon fiber 4.37 MPa, and steel fiber showing the highest value of 4.94 MPa, following the overall trend of steel fiber > carbon fiber > glass fiber > plain concrete. Steel fibers provide the greatest improvement, followed by carbon and glass fibers. Primarily, this improvement is due to the crack bridging ability of fibers. Fibers have a positive effect on post-cracking load transfer and delay cracking in the form of crack widening, as they transfer stresses across cracks and delay crack propagation. Smaller reductions in tensile strength for fiber reinforced marine mixes indicate that fibers can prevent both the initial formation and progression of cracks caused by marine exposure.

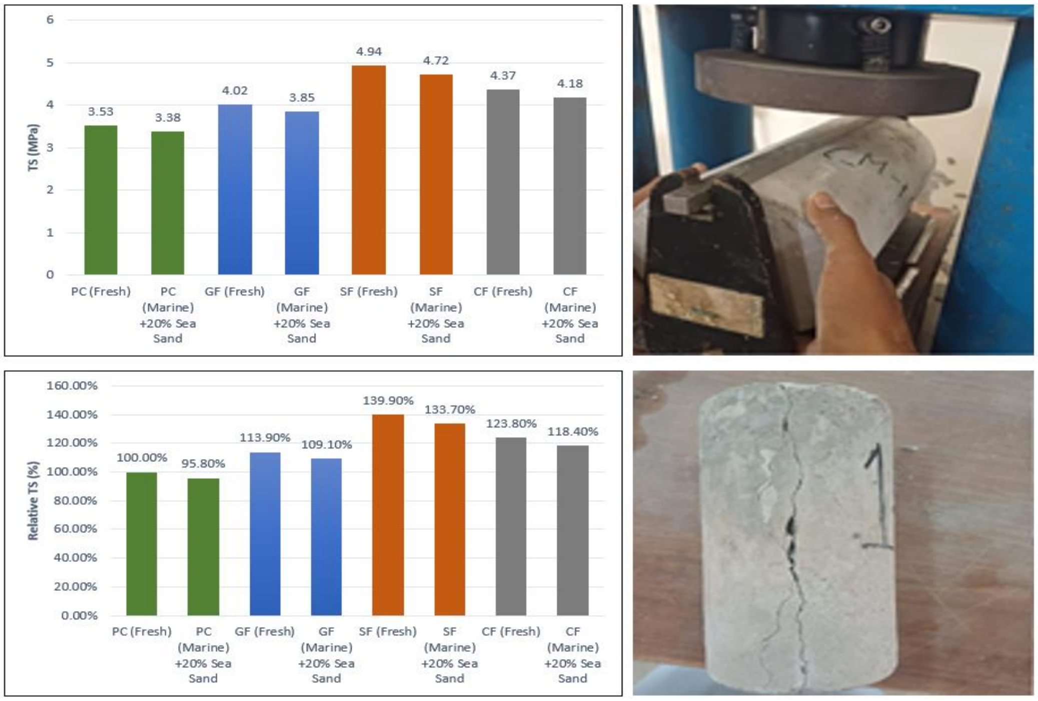

Figure 7: Tensile Strength Failure Pattern and Test Results

4.1.5 Flexural Strength

The flexural strength test data in fig. 8 indicate that marine curing resulted in lower flexural strengths for the plain concrete when compared to the control mixture, where the control mix showed 3.95 MPa and the marine mix reduced to 3.65 MPa, which is a 7.6% decrease due to a weakened matrix and increased pore structure, and all three types of fiber-reinforced concretes performed significantly better than plain concrete regardless of the curing condition As shown in Figure 8, the steel fiber reinforced concrete exhibited the greatest flexural strength, followed by the carbon fiber and then the glass fiber reinforced mixes, with glass fiber reaching 4.54 MPa, carbon fiber 5.44 MPa, and steel fiber showing the highest value of 6.21 MPa, following the overall trend of steel fiber > carbon fiber > glass fiber > plain concrete. The reason behind this phenomenon is attributed to post-cracking response, i.e., as cracks develop and open during loading, fibers can bridge these openings to prevent them from expanding further which enhances the structural member's ability to carry a greater load, thereby improving load carrying capacity. In addition, the fibers help to enhance the structural integrity of the material at cracking. Steel fibers had the best pullout resistance and therefore were the most effective at resisting this type of failure. Carbon fibers produced an excellent level of but superior in terms of corrosion resistance. Glass fibers also helped to improve crack resistance in comparison to plain concrete but did so at a lesser degree than either the carbon or steel fibers.

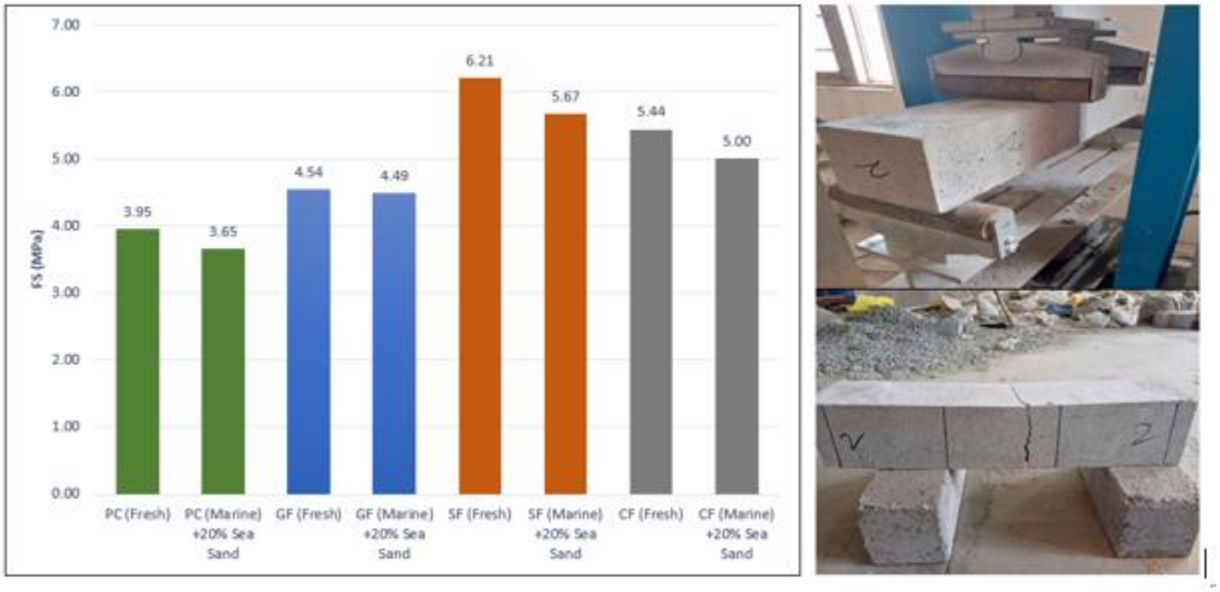

Figure 8: Flexural Strength Testing and Result Trend

4.1.6 Ultrasonic Pulse Velocity

The following figure shows the Ultrasonic Pulse Velocity of all mixes.

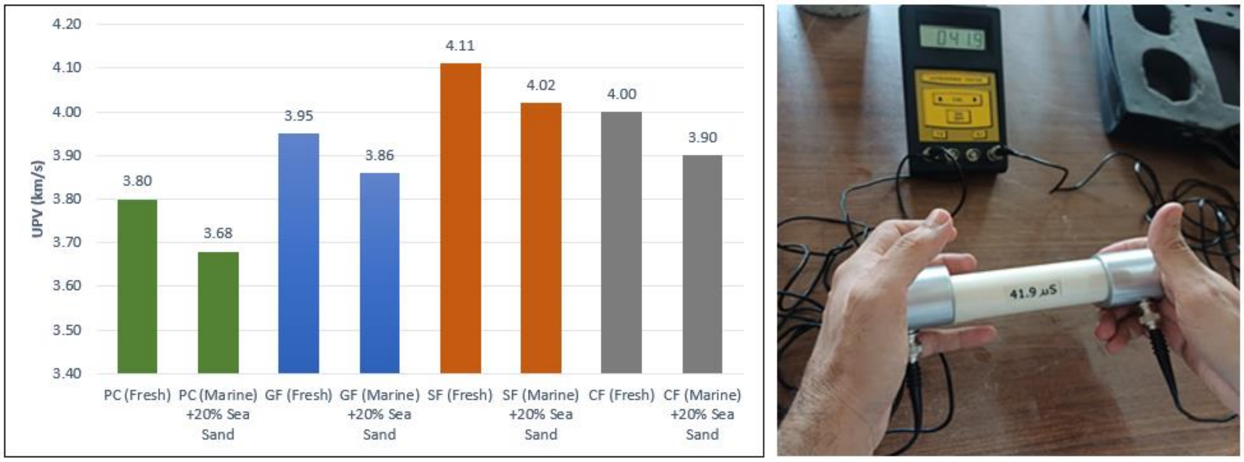

Figure 9: UPV Trend and Test Performance

The ultrasonic pulse velocity results for marine plain concrete were significantly less than those of the control mixture, where the control mix showed 3.80 km/s and the marine mix reduced to 3.68 km/s due to increased voids and microcracks, in order to show a decrease in the internal continuity of the concrete resulting from the marine materials present within it. The data in Figure 9 clearly indicates that the fiber reinforced mixes were significantly greater than their non-fiber counterparts under each of the two curing conditions, with glass fiber reaching 3.95 km/s, carbon fiber 4.00 km/s, and steel fiber showing the highest value of 4.11 km/s, thus the internal integrity of the fiber reinforced mixes was superior, with fewer microcracks forming than in the non-fiber reinforced mixes and following the overall trend of steel fiber > carbon fiber > glass fiber > plain concrete. While the effects of marine curing did have an impact on pore structure development (decreasing UPV) for all mixes, the inclusion of fibers into these mixes successfully limited crack formation and maintained or increased the continuity of the matrix, as the increase in velocity indicates a more compact and dense internal structure with fewer microcracks, thereby decreasing the negative impacts of marine curing.

4.1.7 Water Absorption

Water absorption data from marine cured samples were used to determine that marine curing increases the absorption of water in plain (unreinforced) concrete, where the control mix had 3.80% and the marine mix increased to 4.25% due to higher salt content and the formation of a more porous microstructure, and thus indicates an increase in permeability and subsequent moisture intrusion into the concrete. Additionally, it was observed that the fiber reinforced mixtures demonstrated a general decrease in overall water absorption as shown in Figure 10, with glass fiber at 3.60%, carbon fiber at 3.50%, and steel fiber showing the lowest value of 3.40%, following the overall trend of steel fiber < carbon fiber < glass fiber < plain concrete.

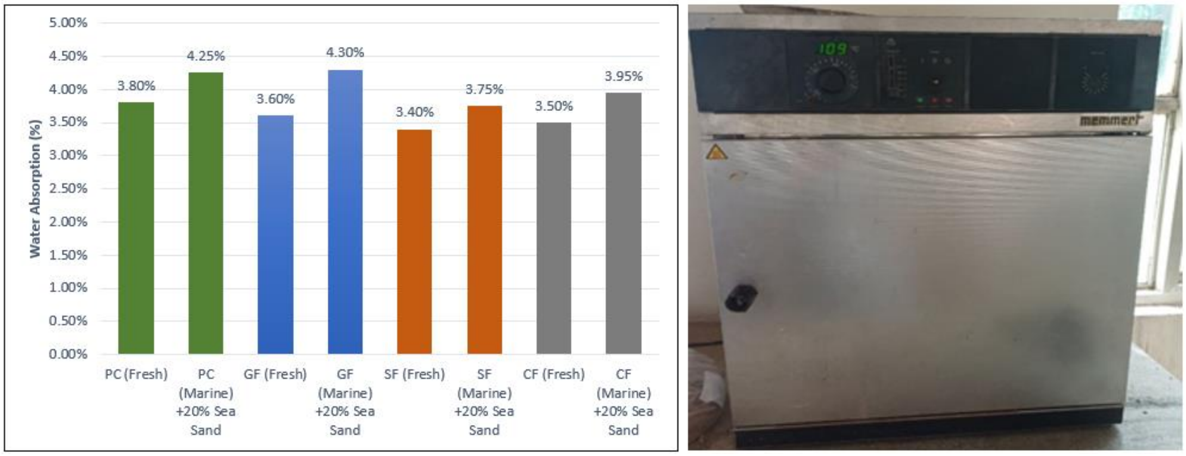

Figure 10: Water Absorption Results and Test Apparatus

Steel fiber reinforced concrete had the least amount of water absorption followed by both the carbon and glass fiber reinforced mixtures. The decrease in absorption for the fiber reinforced mixtures can be attributed to the improved crack control due to the presence of fibers and their contribution to a denser internal structure, as steel fibers reduce capillary pore connectivity and limit water penetration. This data combined with the trend observed with the UPV further supports the impact of fiber reinforcement on improving the durability related performance of concrete when exposed to marine conditions.

4.2 Impact Resistance

The drop weight test data provided on impact resistance show that marine curing significantly decreased the resistance of unreinforced concrete, where the control mix showed 31 blows to failure and the marine mix reduced to 24 blows due to increased brittleness, resulting in lower failure energy for all samples cured at sea. The data presented in Fig. 11 also indicate that all three types of fiber reinforcements improved the performance of plain concrete against impact damage, with glass fiber reaching 160 blows, carbon fiber 190 blows, and steel fiber showing the highest value of 215 blows, following the overall trend of steel fiber > carbon fiber > glass fiber > plain concrete. In addition, steel fiber reinforced concrete showed the most significant increase in resistance to impact compared to carbon and glass fiber reinforced concrete, while glass fibers resulted in a moderately improved impact-resistant composite material. Fiber reinforced composites exhibited significantly greater toughness and residual energy absorption properties than did unreinforced composite materials, as fibers increase energy absorption capacity and improve post-crack behavior of concrete. Marine curing decreased impact resistant properties for all three composite systems; however, the energy absorbing capabilities of each system were still superior to that of unreinforced concrete. Steel fibers produced the highest level of energy absorption as a result of their significant mechanical anchoring within the matrix and very high tensile strength. Carbon fibers retained their consistently high levels of impact resistance after marine exposure because of their corrosion resistant nature and their excellent capability to prevent cracking from propagating through the matrix.

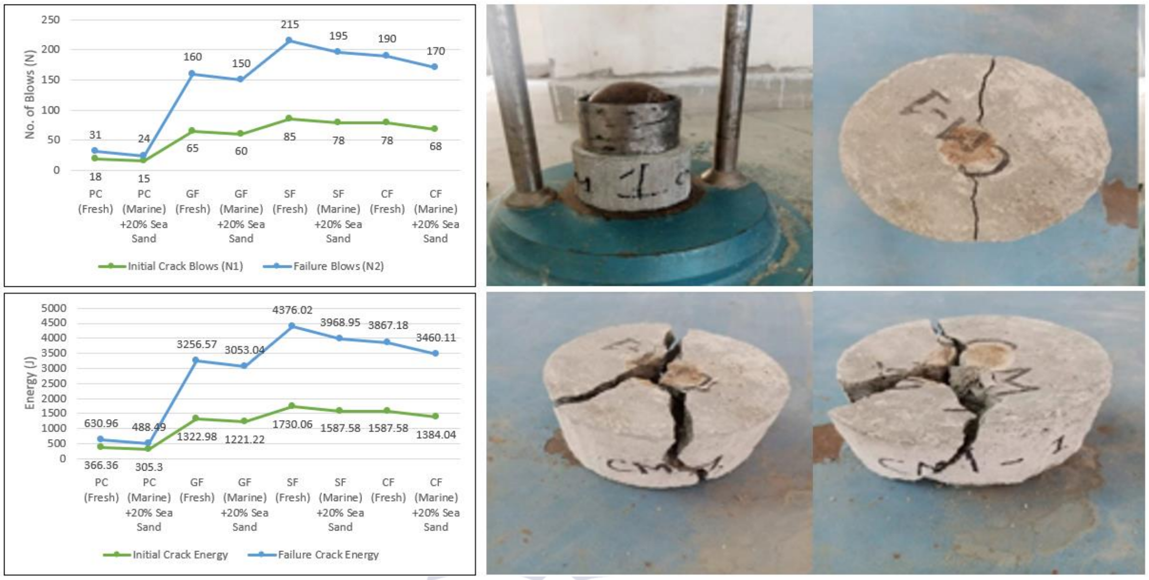

Figure 11: Impact Resistance Results and Test Samples

5. Conclusions & Recommendations

This study evaluated the mechanical performance and durability of fiber reinforced concrete that used a combination of two marine-based materials; specifically, the use of seawater as a curing medium for the specimens and 20% substitution of river sand with sea sand in the mixtures. Based on the experimental results after the 28-day test period, the following conclusions were made by this study regarding the mixes:

- Plain concrete that was cured using 20 percent substitution of river sand by sea sand exhibited an increase in its sensitivity to fresh, mechanical, durability related, and impact performance under marine conditions compared to other types of concrete (indicating decreased performance), as evidenced by reductions in compressive strength (39.5 MPa to 36.5 MPa), tensile strength (3.53 MPa to 3.38 MPa), flexural strength (3.95 MPa to 3.65 MPa), impact resistance (31 to 24 blows), and UPV (3.80 km/s to 3.68 km/s), along with an increase in water absorption (3.80% to 4.25%) due to increased porosity, microcracking, and interference of chloride and sulphate ions with hydration.
- Discrete fibers within the concrete reduced the loss of performance when the curing process utilized a marine based material, as well as improved the performance of the concrete under freshwater or marine curing conditions, by arresting crack formation, limiting crack propagation, improving stress redistribution, and enhancing internal matrix continuity.
- Steel Fiber Reinforced Concrete (SFRC) was shown to have a greater increase in Compressive Strength, Splitting Tensile Strength, Flexural Strength, and Impact Resistance compared to other types of fiber reinforcement tested; Carbon Fiber Reinforced Concrete (CFRC) had the next greatest increases in all properties; Glass Fiber

Reinforced Concrete (GFRC), however, only showed modest increases in all of these properties, with overall performance trends consistently observed as: steel fiber > carbon fiber > glass fiber > plain concrete across all mechanical properties.

- Durability related measures indicated that marine curing resulted in an increase in water absorption and reduction in Ultrasonic Pulse Velocity (UPV) for the control specimens, but did result in limiting moisture penetration and maintaining higher levels of internal quality in the fiber reinforced specimens under marine exposure conditions, as fibers reduced capillary pore connectivity, decreased voids, and produced a denser and more compact microstructure.
- The post-crack energy absorption and impact resistance of fiber reinforced concretes cured using seawater conditions (or other curing conditions) were greatly improved as a result of fiber reinforcement; the steel fibers provided the best toughness and energy dissipation capabilities due to strong mechanical anchorage and high tensile strength, while the carbon and glass fibers provided the next highest amount of toughness and energy dissipation capabilities, with fibers significantly enhancing post-cracking behavior and residual load carrying capacity.
- The improvement in all mechanical and durability properties is primarily attributed to the crack bridging ability of fibers, their role in delaying crack initiation and widening, and their effectiveness in transferring stresses across cracks, thereby mitigating the adverse effects of marine exposure such as formation of ettringite, and increased pore structure.

In general, the test results suggest that, where appropriate amounts of fibers have been incorporated into seawater cured FRC (fiber reinforced concrete) utilizing a part replacement of river sand with sea sand, the mechanical characteristics and durability of such FRC may be satisfactory; therefore, suitable for use in coastal or resource limited areas. However, additional research will be needed to assess the long-term durability of this type of material in real marine environments and to examine hybrid fiber systems, various levels of sea sand replacement, and differing sources of seawater. Advanced microscopic structural characterization of this type of material and life cycle costing assessments should also be conducted to provide practical implementation guidance for the use of sustainable materials in marine structures.

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