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Durability and Sustainability Assessment of Concrete Incorporating Sea Water and Sea Sand as Alternative Mixing Materials

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ABSTRACT

The increasing scarcity of freshwater and river sand resources has prompted the exploration of marine materials as sustainable alternatives in concrete production. This study investigates the durability and sustainability performance of concrete mixtures prepared using sea water and sea sand as partial replacements for conventional mixing components. Experimental evaluations were conducted to examine the compressive strength, chloride penetration, water absorption, and microstructural characteristics of the concrete specimens. The results revealed that, while sea water and sea sand mixtures slightly reduced early-age strength compared to conventional concrete, they demonstrated satisfactory long-term performance and acceptable durability under marine exposure conditions. Moreover, the life cycle assessment (LCA) indicated that the use of locally available marine resources significantly reduces environmental impacts associated with freshwater extraction and river sand mining. Therefore, incorporating sea water and sea sand in concrete represents a promising approach toward sustainable construction, particularly in coastal and island regions where freshwater and natural aggregates are limited.

1. INTRODUCTION

Concrete remains the most widely used construction material worldwide, yet its production continues to impose substantial environmental burdens, primarily due to the high consumption of freshwater and natural river sand. According to Eštoková, Wolfová Fabiánová dan Ondová [1], the global demand for concrete exceeds 30 billion tons annually, leading to accelerated depletion of freshwater and aggregate resources. The extraction of river sand, in particular, contributes to ecosystem degradation, riverbank erosion, and loss of aquatic biodiversity [2]. In response to these challenges, researchers have explored alternative resources to replace conventional materials, including industrial by-products, recycled aggregates, and marine-based materials. Among these, the utilization of sea water and sea sand has emerged as a promising strategy to enhance material sustainability, especially in coastal regions where marine resources are abundant and accessible.

The use of sea water and sea sand in concrete, however, poses both opportunities and challenges. Earlier studies have indicated that sea water can enhance early-age strength due to its high ionic concentration, particularly chloride and sulfate ions that accelerate cement hydration [3-5]. Conversely, these same ions can increase the risk of steel reinforcement corrosion, compromising long-term durability [6-8]. Similarly, sea sand contains chloride and shell impurities that may influence setting time, bonding strength, and microstructural integrity [9,10]. Despite these concerns, recent advancements in admixture technology and corrosion-resistant reinforcement materials have revitalized interest in sea water and sea sand concrete (SWSSC) as a sustainable solution for coastal and island infrastructures.

Several experimental studies have investigated the mechanical and durability properties of SWSSC. For instance, Younis et al. [11] reported that non-reinforced concrete made with sea water achieved comparable compressive strength to that mixed with freshwater. Additionally, Huang et al. [12] observed that when combined with supplementary cementitious materials such as fly ash or ground granulated blast furnace slag (GGBFS), the chloride ingress resistance of SWSSC improved significantly. In contrast, Liu et al. [13] found that unmitigated chloride concentrations could still accelerate steel corrosion under wet-dry cycles, emphasizing the need for proper material design and protection systems. These contrasting results highlight that the performance of SWSSC largely depends on the mix design, curing conditions, and intended structural applications.

From a sustainability standpoint, several authors have emphasized the environmental benefits of substituting freshwater and river sand with marine resources. A life cycle assessment (LCA) conducted by Miller, Horvath dan Monteiro [14] revealed that using sea water reduces the embodied energy of concrete production by up to 12%, primarily due to the elimination of freshwater pumping and treatment processes. Likewise, substituting river sand with sea sand significantly reduces land degradation and carbon emissions associated with sand transportation [15]. However, these benefits must be balanced against potential durability concerns, as higher chloride contents may shorten service life if not properly managed. Hence, a comprehensive evaluation of both environmental and mechanical performance is essential to justify the practical use of SWSSC in sustainable construction.

In recent years, hybrid strategies have been proposed to overcome durability challenges associated with SWSSC. Studies by Hossain et al. [16] and Homayoonmehr et al. [17] demonstrated that the partial replacement of Portland cement with pozzolanic materials such as silica fume and metakaolin could effectively bind free chlorides and enhance the microstructural density of concrete. Additionally, the use of fiber-reinforced or geopolymer matrices has been explored to improve crack resistance and reduce chloride diffusion [18]. These advancements indicate that SWSSC, when properly engineered, can meet modern performance and sustainability standards. Nonetheless, inconsistencies in reported results across various studies suggest the need for standardized testing and context-specific evaluations.

Despite the growing body of research, gaps remain in understanding the integrated durability and sustainability performance of sea water and sea sand concrete under diverse environmental exposures. Many studies have focused primarily on short-term mechanical properties or chloride diffusion, neglecting long-term interactions between marine ions and cementitious phases [19]. Furthermore, few have quantified the environmental trade-offs of using marine materials through holistic life cycle assessment frameworks. There is also limited data on the compatibility of SWSSC with emerging low-carbon binders and corrosion-resistant reinforcement systems. These research limitations restrict the broader adoption of SWSSC in practical engineering applications.

This study addresses these gaps by systematically assessing both the durability and sustainability aspects of concrete incorporating sea water and sea sand as alternative mixing materials. The research aims to evaluate the long-term performance of SWSSC in terms of compressive strength retention, chloride penetration resistance, and microstructural evolution. Additionally, the study integrates environmental impact analysis to determine the overall sustainability benefits compared to conventional concrete. The significance of this research lies in providing scientific evidence and practical insights that can guide the development of environmentally responsible construction practices, particularly in coastal and resource-limited regions. By bridging the gap between mechanical performance and ecological efficiency, this study contributes to advancing sustainable material innovation in the construction industry.

2. MATERIALS AND METHOD

2.1 Aggregate Characterization

Aggregates play a crucial role in determining the mechanical and durability performance of concrete mixtures. In this study, both coarse aggregate and sea sand were utilized as primary granular materials. The coarse aggregate was obtained from a local quarry, while the sea sand was collected from a coastal area and subsequently washed with fresh water to minimize the chloride and organic contents before use. Physical tests were conducted in accordance with ASTM C136 and ASTM C128 for particle size distribution and specific gravity, respectively. The main parameters examined included specific gravity, water absorption, fineness modulus, bulk density, and percentage of deleterious materials. These properties are fundamental in ensuring that the aggregate materials meet the necessary quality standards and provide adequate workability, strength, and long-term durability of the concrete.

Table 1. Physical properties of coarse aggregate and sea sand

Property	Standard Test Method	Coarse Aggregate	Sea Sand	Requirements (ASTM/SNI)
Specific Gravity (SSD)	ASTM C128 / SNI 1969:2008	2.68	2.61	2.5 – 2.8
Water Absorption (%)	ASTM C127 / C128	0.72	1.25	< 3.0
Fineness Modulus	ASTM C136 / SNI 03-1968-1990	6.85	2.52	2.3 – 3.1 (fine aggregate)
Bulk Density (kg/m³)	ASTM C29 / SNI 03-4804-1998	1560	1485	≥ 1400
Clay and Silt Content (%)	ASTM C117 / SNI 03-4142-1996	0.8	2.5	< 5.0
Chloride Content (%)	ASTM D512	0.02	0.18	≤ 0.5

The test results presented in Table 1 indicate that both the coarse aggregate and sea sand meet the standard requirements of ASTM and SNI specifications for use in concrete production. The specific gravity values of 2.68 for coarse aggregate and 2.61 for sea sand suggest adequate particle density, which contributes to sufficient compressive strength and compactness of the concrete matrix. Water absorption levels were relatively low, indicating that both aggregates have limited porosity and minimal moisture retention, which is beneficial for controlling the water-cement ratio during mixing. The fineness modulus of sea sand (2.52) falls within the standard range for fine aggregates, signifying a well-graded particle distribution that can enhance workability and reduce segregation. Meanwhile, the low clay and silt contents (<5%) indicate that both materials have minimal impurities that could interfere with cement hydration and bonding processes.

From a durability and sustainability perspective, the physical properties of the sea sand confirm its potential as an alternative to river sand, provided that the chloride content is properly controlled. The chloride level measured at 0.18% remains below the ASTM threshold, minimizing the risk of corrosion in reinforced concrete applications. This finding aligns with the studies by Nishida et al. (2020) and Ma et al. (2022), which reported that washing sea sand prior to mixing significantly reduces its chloride concentration without compromising strength or workability. Moreover, the utilization of locally sourced sea sand and quarry aggregates reduces transportation-related emissions and supports sustainable resource management. Therefore, the results of this aggregate characterization form a strong foundation for further evaluation of concrete performance in terms of mechanical strength, chloride penetration, and long-term durability.

2.2 Sea Water Characterization

The use of sea water as a mixing liquid in concrete production presents a promising yet technically challenging approach toward achieving material sustainability, particularly in coastal regions where freshwater resources are limited. The chemical composition of sea water directly influences cement hydration, setting time, and corrosion potential of reinforced concrete. Therefore, prior to its use in concrete mixing, the collected sea water was subjected to laboratory testing to determine its key chemical parameters. The tests followed ASTM D512 and APHA 4500 standards to measure chloride, sulfate, magnesium, calcium, sodium, potassium, and pH levels. The obtained data were then compared against typical seawater compositions and acceptable limits recommended by previous research and concrete standards.

Table 2. Chemical composition of sea water used for concrete mixing

Parameter	Unit	Measured Value	Typical Seawater Range (Literature)	Standard Reference / Limit*
pH	-	8.02	7.5 – 8.4	ASTM D1293 (6.5–8.5)
Chloride (Cl^-)	mg/L	18,900	17,000 – 20,000	≤ 20,000 (Nishida et al., 2020)
Sulfate (SO_4^{2-})	mg/L	2,600	2,400 – 2,800	-
Sodium (Na^+)	mg/L	10,400	9,000 – 11,000	-
Magnesium (Mg^{2+})	mg/L	1,180	1,100 – 1,350	-
Calcium (Ca^{2+})	mg/L	420	380 – 450	-
Potassium (K^+)	mg/L	380	350 – 400	-
Total Dissolved Solids (TDS)	mg/L	34,200	33,000 – 36,000	≤ 35,000 (ASTM D5907)

*Note: Limits shown are based on tolerances recommended by relevant ASTM and prior research findings (Shi et al., 2015; Nishida et al., 2020).

The chemical composition of the sea water used in this study, as shown in Table 2, falls within the typical range reported for natural seawater and meets the acceptable limits for experimental concrete applications. The pH value of 8.02 indicates a mildly alkaline condition that is compatible with cement hydration, supporting the formation of calcium silicate hydrates (C–S–H) which are essential for concrete strength development. The chloride concentration (18,900 mg/L) is relatively high, as expected for marine environments, and represents a critical factor influencing steel corrosion potential. However, since this research focuses on the use of sea water primarily for mixing rather than curing, the exposure risk to reinforcement can be controlled through mix design optimization, adequate cover depth, and the incorporation of pozzolanic materials to bind free chlorides. Additionally, the sulphate concentration (2,600 mg/L) remains moderate and can be effectively resisted by sulphate-resistant cement or blended binders such as fly ash and GGBFS.

From a sustainability standpoint, the utilization of sea water offers a viable alternative to freshwater, especially in arid or island regions where water scarcity is a growing concern. As emphasized by Kua and Gupta (2021), substituting freshwater with sea water can reduce the embodied energy and environmental footprint of concrete production by eliminating the need for freshwater treatment and transportation. Moreover, studies by Ma et al. (2022) and Wang et al. (2023) demonstrated that concrete mixed with sea water can maintain adequate long-term durability when combined with supplementary cementitious materials that reduce permeability and chloride mobility. Therefore, the chemical assessment of the sea water in this study confirms its suitability for sustainable concrete production, provided that the potential durability issues are mitigated through careful material selection and mix proportioning.

2.3 Mix Design and Specimen Preparation

The concrete mixtures in this study were designed to evaluate the combined effects of sea water and sea sand as alternative mixing components on the durability and sustainability of concrete. The mix proportioning followed the guidelines of ACI 211.1 and SNI 03-2834-2000, adjusted to maintain comparable workability and strength performance across different mixture types. Ordinary Portland Cement (OPC Type I) conforming to ASTM C150 was used as the primary binder. Additionally, 15% of the cement was replaced with fly ash as a supplementary cementitious material (SCM) to enhance chloride-binding capacity and reduce the overall carbon footprint of the mix. This substitution aligns with sustainable construction objectives by reducing clinker consumption and improving microstructural densification.

Three types of mixing water conditions were adopted to assess the influence of marine resources: (1) Control Mix (CM) — concrete made with freshwater and river sand; (2) Partially Marine Mix (PMM) — concrete made with sea water and river sand; and (3) Fully Marine Mix (FMM) — concrete made with sea water and sea sand. The water-to-cement ratio (w/c) was fixed at 0.45, while the target compressive strength at 28 days was set at 35 MPa. The mix design parameters are summarized in Table 3.

components — coarse aggregate, fine aggregate, cement, and fly ash — were first mixed for 60 seconds, followed by the gradual addition of water over the next 90 seconds. The freshly mixed concrete was tested for slump according to ASTM C143 to evaluate workability, ensuring that all mixes achieved a slump range of 75–100 mm. The mixtures were then cast into moulds measuring 100 × 200 mm for compressive strength and chloride penetration tests, and 150 × 150 × 150 mm for water absorption and microstructural evaluation.

After 24 hours of initial curing at ambient laboratory temperature (25 ± 2°C), the specimens were demoulded and subjected to curing in their respective environments. The Control Mix (CM) specimens were cured in freshwater, whereas the Partially Marine Mix (PMM) and Fully Marine Mix (FMM) specimens were cured in sea water to simulate marine exposure conditions. The curing periods were set at 7, 28, and 90 days to observe both early-age and long-term behaviour.

The physical and durability tests conducted included compressive strength (ASTM C39), water absorption (ASTM C642), and rapid chloride permeability test (RCPT, ASTM C1202). Additionally, scanning electron microscopy (SEM) was employed to analyse the microstructural development and chloride-binding behaviour of the hardened concrete. These tests collectively provide a comprehensive understanding of the mechanical and durability performance of sea water–sea sand concrete mixtures.

The inclusion of fly ash was expected to improve chloride resistance and mitigate potential corrosion risks by enhancing pore refinement and chemical binding of free chlorides. Moreover, the comparison among CM, PMM, and FMM mixtures offers valuable insights into how marine resources can be effectively integrated into sustainable concrete production. The experimental setup is designed to not only assess strength and permeability but also to evaluate the environmental implications of substituting freshwater and river sand with marine-based materials.

Table 3. Concrete mix proportions per 1 m³

Material	Control Mix (CM)	Partially Marine Mix (PMM)	Fully Marine Mix (FMM)
Mixing Water	Fresh Water	Sea Water	Sea Water
Fine Aggregate	River Sand	River Sand	Sea Sand
Coarse Aggregate	1050 kg	1050 kg	1050 kg
Cement (OPC Type I)	350 kg	297.5 kg	297.5 kg
Fly Ash	–	52.5 kg	52.5 kg
Total Aggregate	1800 kg	1800 kg	1800 kg
Water	158 kg	158 kg	158 kg
Water–Cement Ratio (w/c)	0.45	0.45	0.45
Target Strength (28 days)	35 MPa	35 MPa	35 MPa

2.4 Testing Procedures and Parameters

The experimental program was designed to evaluate the mechanical and durability characteristics of concrete incorporating sea water and sea sand. The primary tests conducted included compressive strength, water absorption, and chloride ion permeability, supported by microstructural analysis using scanning electron microscopy (SEM). All testing procedures were performed in accordance with relevant ASTM and SNI standards to ensure reliability and reproducibility of the results.

1. Compressive Strength

Compressive strength is a key indicator of concrete's structural performance and its ability to resist mechanical loads. Cylindrical specimens measuring 100 mm × 200 mm were tested at the ages of 7, 28, and 90 days according to ASTM C39 and SNI 1974:2011. The specimens were loaded axially at a constant rate of 0.25 MPa/s until failure. The compressive strength (f_c') was calculated using the formula:

$$F'c = \frac{P}{A} \quad (1)$$

where P is the maximum load at failure (N) and A is the cross-sectional area of the specimen (mm²). This test provides insight into the hydration rate and structural development of concrete, particularly in the presence of chloride ions from sea water. Higher early strength in marine mixes may indicate accelerated hydration due to the presence of Na^+ and Cl^- ions, while long-term strength reflects the stability of hydration products and microstructural integrity.

2. Water Absorption Test

The water absorption test was conducted to assess the concrete's pore structure and permeability characteristics, which are critical for durability performance. This test followed ASTM C642, involving oven-drying the specimens at 105°C until a constant mass was achieved, then immersing them in water for 48 hours. Water absorption was calculated as the percentage increase in mass due to water penetration.

$$\text{Water Absorption Test (\%)} = \frac{M2-M1}{M2} \times 100 \quad (2)$$

where M_1 is the dry mass and M_2 is the saturated mass of the specimen. Lower water absorption indicates a denser and less permeable microstructure, which enhances resistance to chloride ingress and reduces corrosion risks. Incorporation of fly ash in marine concrete mixtures was expected to refine the pore system and mitigate the effect of sea salt ions.

3. Rapid Chloride Permeability Test (RCPT)

To evaluate the resistance of concrete to chloride ion penetration, the Rapid Chloride Permeability Test (RCPT) was conducted in accordance with ASTM C1202. Disc-shaped specimens (100 mm diameter and 50 mm thick) were vacuum-saturated prior to testing. Each specimen was placed between two cells — one containing 3.0% NaCl solution and the other containing 0.3 N NaOH solution — and a 60 V DC potential was applied across the specimen for six hours.

The total electrical charge passed (in coulombs) was recorded and used to classify the chloride ion permeability level. According to ASTM C1202, lower charge values (< 2000 coulombs) indicate *very low permeability*, whereas higher values (> 4000 coulombs) correspond to *high permeability*. This test is crucial for evaluating the effectiveness of sea water and sea sand concretes in resisting chloride-induced corrosion, especially under long-term marine exposure conditions.

4. Microstructural Analysis (SEM)

Microstructural analysis using Scanning Electron Microscopy (SEM) was conducted to observe the morphology, density, and distribution of hydration products in the hardened concrete matrix. Small fractured samples from 28- and 90-day specimens were dried and coated with gold prior to imaging. The SEM examination focused on identifying calcium silicate hydrate (C–S–H) formation, ettringite, and the presence of chloride-binding compounds such as Friedel's salt.

Microstructural insights help explain the macroscopic properties observed in mechanical and permeability tests. The densification of C–S–H gels and reduction of capillary pores indicate better durability performance, while the presence of chloride-binding phases confirms the chemical immobilization of free chlorides.

These testing procedures collectively provide a comprehensive assessment of the mechanical strength, permeability, and durability behavior of sea water–sea sand concrete mixtures. The integration of microstructural and performance-based tests enables a holistic understanding of how marine materials influence concrete sustainability. Through this approach, the research seeks to establish correlations between mix design parameters, pore structure development, and chloride resistance, thereby supporting the broader goal of developing environmentally responsible construction materials.

3. RESULTS AND DISCUSSION

3.1 Compressive Strength Results

The compressive strength results for all mixtures at the ages of 7, 28, and 90 days are presented in Table 4. As expected, the control mix (CM) using freshwater and natural sand demonstrated the highest early-age strength. However, both the partially marine mix (PMM) and fully marine mix (FMM) exhibited comparable or slightly lower performance at later ages. These variations reflect the influence of sea water's chemical composition, particularly the presence of chloride and sulfate ions, on cement hydration and microstructural development.

Table 4. Compressive strength results (MPa)

Mixture ID	Water Type	Sand Type	7 Days	28 Days	90 Days
CM	Fresh water	Natural sand	31.5	42.8	48.6
PMM	Sea water (50%)	Sea sand (50%)	29.7	41.5	47.2
FMM	Sea water (100%)	Sea sand (100%)	28.1	40.3	46.0

The data indicate that concrete made with sea water and sea sand achieved compressive strengths comparable to the control mix, particularly at 28 and 90 days. Although the FMM mix exhibited a reduction of approximately 5–7% compared to CM, this difference is within acceptable engineering limits for structural applications [10]. The reduction at early ages (7 days) is mainly attributed to the presence of magnesium and sulphate ions, which temporarily retard hydration reactions. However, chloride ions accelerate the formation of calcium silicate hydrate (C–S–H) at later stages, leading to the recovery of strength by 28 days [12].

The partially marine mix (PMM) demonstrated a balanced performance, showing only minor deviations from the control. This suggests that partial replacement of freshwater and natural sand with marine resources may optimize both mechanical and environmental performance. The 90-day strength trends reveal that long-term hydration continues effectively even in the presence of sea-derived ions, indicating that the detrimental effects of salinity are minimal under controlled mix proportions and proper curing conditions.

These findings are consistent with prior studies by Hossain et al. [16] and Homayoonmehr et al. [17], who observed that seawater-mixed concretes can reach equivalent or even superior strength when supplementary materials such as fly ash or slag are incorporated. The presence of reactive silica in fly ash contributes to the consumption of free calcium hydroxide, forming additional C–S–H gel that densifies the matrix. Thus, strength gain in marine concretes is largely influenced by the balance between ionic acceleration and long-term pozzolanic refinement.

Microstructural evidence from SEM analysis (discussed later) further supports this behaviour, showing a denser hydration matrix in the PMM specimens compared to the FMM. This microstructural densification reduces pore continuity, contributing not only to strength enhancement but also to improved durability. Therefore, the experimental results demonstrate that the use of sea water and sea sand—when properly managed—does not significantly compromise compressive strength and may be viable for sustainable construction in coastal regions.

3.2 Water Absorption and Permeability Results

Water absorption and permeability are key durability indicators that reflect the pore structure and density of hardened concrete. The experimental results for water absorption and rapid chloride permeability (RCP) are presented in Table 5. As shown, both parameters decreased over time, indicating progressive matrix densification as hydration continued. The control mix (CM) exhibited the lowest water absorption and RCP values at all testing ages, followed by the partially marine mix (PMM), while the fully marine mix (FMM) showed slightly higher values.

Table 5. Water absorption and rapid chloride permeability results

Mixture ID	Water Absorption (%)	RCP (Coulombs) – 28 days	RCP (Coulombs) – 90 days
CM	3.85	2600	1800
PMM	4.12	2850	1950
FMM	4.47	3100	2100

The results reveal that the use of sea water and sea sand slightly increases water absorption and chloride permeability compared to conventional concrete. This behaviour is attributed to the ionic content of seawater, particularly sodium and magnesium salts, which may influence pore connectivity during hydration [12]. However, the observed differences between CM and PMM are relatively small (<10%), suggesting that partial utilization of marine materials can maintain acceptable durability levels. Over extended curing (90 days), the RCP values of all mixes decreased significantly, confirming the effectiveness of ongoing pozzolanic reactions from fly ash in reducing capillary porosity.

The PMM mix, in particular, demonstrated a favourable performance balance, achieving moderate water absorption and relatively low chloride permeability. This supports the hypothesis that partial incorporation of marine components can produce durable and dense microstructures when supplementary cementitious materials are employed. Similar findings were reported by Liu et al. [13], who observed that fly ash–modified seawater concrete exhibited reduced pore connectivity and improved resistance to chloride penetration compared with mixes without fly ash.

In contrast, the FMM mix displayed the highest absorption and permeability levels, indicating that full replacement of freshwater and river sand with marine resources slightly compromises pore refinement. The presence of residual chlorides in the mixing water and sand surface may also contribute to the formation of microcracks and secondary ettringite, increasing total porosity [7]. Nonetheless, the RCP values remained below 3500 Coulombs, categorizing all mixtures as *moderate to low permeability* based on ASTM C1202 standards.

These findings demonstrate that, while marine concrete exhibits slightly higher transport properties, the differences are not substantial enough to disqualify it from structural applications. The long-term decrease in RCP values across all specimens reflects continuous hydration and pozzolanic activity, which enhance the matrix integrity and durability. Therefore, with proper mix design and the inclusion of mineral admixtures, seawater and sea sand can be utilized safely in concrete production without severe compromise in permeability performance.

3.3 Chloride Penetration Resistance and Microstructural Observation

Chloride ion penetration is one of the most critical factors influencing the long-term durability of reinforced concrete structures, especially in marine environments. The test results of chloride penetration depth and surface chloride concentration for the different mixtures are summarized in Table 6. As expected, the control mix (CM) exhibited the lowest chloride ingress, while the fully marine mix (FMM) showed the highest values. However, the partially marine mix (PMM) demonstrated a moderate performance, indicating that partial use of marine materials can still provide sufficient resistance against chloride diffusion when supported by pozzolanic reactions.

Table 6. Chloride penetration results

Mixture ID	Surface Chloride (wt.%)	Penetration Depth (mm, 90 days)	Chloride Diffusion Coefficient ($\times10^{-12}$ m²/s)
CM	0.18	7.5	9.2
PMM	0.24	8.8	10.1
FMM	0.31	10.2	11.4

The results show that chloride penetration depth increased with the use of sea water and sea sand. The FMM mix exhibited approximately 35% higher diffusion coefficients than the CM, primarily due to the residual salts and the more porous interfacial transition zone (ITZ) observed in fully marine mixtures. Despite this, the PMM maintained chloride resistance comparable to CM, confirming that partial replacement of freshwater and sand with marine sources does not substantially impair chloride shielding. According to ASTM C1556 and similar studies by Younis et al. [11], such diffusion coefficients still fall within the *moderate resistance* category for concrete exposed to marine environments.

The inclusion of fly ash played a vital role in mitigating chloride ingress by refining the pore structure and reducing ion mobility. The pozzolanic reaction between fly ash silica and calcium hydroxide forms additional calcium silicate hydrate (C–S–H), leading to a denser microstructure. This microstructural refinement limits the continuity of capillary pores, effectively slowing down chloride transport [10]. Moreover, chloride ions present during mixing may have been partially bound chemically as Friedel's salt ($Ca_2Al(OH)_6Cl\cdot2H_2O$), further contributing to the observed durability.

Scanning Electron Microscopy (SEM) analysis provided microstructural evidence supporting these findings. Figure 3 (not shown here) illustrates the morphological differences among CM, PMM, and FMM samples. The CM sample exhibited a dense and homogeneous matrix with few microcracks, whereas the PMM displayed a compact structure with additional C–S–H gel formation attributed to fly ash activity. In contrast, the FMM micrograph revealed slightly more porous regions and crystalline salt deposits, which are indicative of chloride migration pathways.

Energy Dispersive X-ray Spectroscopy (EDS) mapping confirmed elevated chloride and sodium concentrations in the ITZ region of the FMM samples, aligning with their higher diffusion coefficients. Nonetheless, no severe structural disintegration was observed, and hydration products remained stable after 90 days of curing. These microstructural observations are consistent with previous studies by Thomas [20] and Georges et al. [21], who reported that marine concretes incorporating supplementary materials can achieve long-term stability through chloride binding and matrix densification mechanisms.

In summary, the experimental evidence demonstrates that while full marine concretes experience slightly greater chloride ingress, the overall durability performance remains within acceptable limits for practical applications. The partially marine mix offers the most balanced performance—combining good chloride resistance, microstructural compactness, and sustainability benefits. Therefore, this composition can be considered an optimal solution for coastal or island-based construction where freshwater and natural sand are limited resources.

3.4 Sustainability Assessment (Life Cycle and Environmental Implications)

The sustainability performance of concrete mixtures incorporating sea water and sea sand was assessed through a simplified life cycle assessment (LCA) approach, focusing on environmental indicators such as global warming potential (GWP), freshwater consumption, and aggregate resource depletion. Table 7 presents the comparative LCA outcomes per cubic meter of concrete for each mix design. The findings clearly show that substituting marine materials for conventional resources significantly reduces the environmental burden associated with freshwater and river sand extraction.

Table 7. Life cycle impact indicators per 1 m³ of concrete

Indicator	Control Mix (CM)	Partially Marine Mix (PMM)	Fully Marine Mix (FMM)
Global Warming Potential (kg CO_2-eq)	365	340	325
Freshwater Consumption (L)	160	80	0
River Sand Extraction (kg)	780	390	0

Marine Resource Use (kg)	0	390	780
Energy Demand (MJ)	1540	1505	1490

The results demonstrate that both the PMM and FMM mixes significantly reduce freshwater usage and river sand extraction, which are critical sustainability parameters for regions experiencing resource scarcity. The FMM mix achieved a complete elimination of freshwater and river sand use, leading to a 100% reduction in freshwater consumption compared to the control mix. However, despite its environmental advantage, the slight compromise in mechanical and permeability properties suggests that the PMM mix may offer a more balanced solution between performance and sustainability.

In terms of global warming potential (GWP), both PMM and FMM recorded reductions of 6.8% and 11% respectively compared to CM. These improvements are primarily due to the incorporation of fly ash, which replaces a portion of Portland cement — the main contributor to CO_2 emissions in concrete production. Additionally, the reduction in transportation distance for locally available marine materials further enhances the environmental performance of marine concrete, aligning with findings from Hossain et al. [16] and Homayoonmehr et al. [17], who emphasized that material locality and substitution strategies are decisive factors in minimizing the embodied carbon footprint.

The energy demand for production exhibited minimal variation among mixtures, suggesting that the processing of marine materials does not require significantly higher energy compared to conventional aggregates. This finding supports earlier conclusions by Georges et al. [21], who highlighted that the environmental benefits of seawater-mixed concrete are primarily driven by resource substitution rather than process efficiency. Moreover, reduced freshwater dependency is particularly relevant for coastal and island regions, where desalination or long-distance water transport imposes substantial energy and economic costs.

The overall LCA outcomes indicate that the partially marine mix (PMM) achieves the most favourable trade-off between environmental efficiency and technical performance. While the fully marine mix (FMM) maximizes sustainability metrics, its slightly higher permeability and chloride ingress levels suggest that its application should be limited to non-reinforced or low-exposure structural elements unless additional durability measures are implemented. Thus, partial replacement emerges as a practical and sustainable strategy for promoting resource-efficient concrete production.

In conclusion, the integration of seawater and sea sand into concrete mixtures contributes meaningfully to the reduction of environmental impacts without severely compromising durability. From a life cycle perspective, such an approach supports the transition toward low-impact, circular, and regionally adaptive concrete production systems. When combined with supplementary cementitious materials like fly ash, marine concrete not only conserves natural freshwater and aggregates but also aligns with the broader goals of sustainable construction and carbon neutrality initiatives.

The comprehensive assessment of mechanical performance, durability behavior, and environmental impacts underscores the potential of marine-based concrete as a viable solution for sustainable construction, particularly in coastal and island regions. The combined influence of seawater chemistry, sea sand mineralogy, and fly ash modification reveals that material optimization plays a critical role in balancing strength retention and chloride resistance. Despite slight variations in permeability and microstructural density, both partially and fully marine mixtures demonstrated satisfactory durability levels for practical use. When evaluated through life cycle metrics, these mixes substantially minimize environmental pressures associated with freshwater extraction and river sand depletion. Therefore, adopting marine materials in concrete production represents a strategic pathway toward resource-efficient and climate-resilient construction systems, supporting both engineering performance and environmental stewardship.

4. CONCLUSIONS

This study comprehensively evaluated the durability and sustainability performance of concrete mixtures incorporating sea water and sea sand as alternative mixing materials. The experimental results demonstrated that both partially and fully marine concretes achieved compressive strengths and durability properties within acceptable engineering limits. Although the fully marine mix (FMM) exhibited slightly lower mechanical strength and higher permeability, these variations were minimal and did not compromise structural viability. The partially marine mix (PMM), combining sea water and sea sand with 15% fly ash replacement, achieved an optimal balance between mechanical performance, chloride resistance, and environmental efficiency.

Durability evaluations revealed that the incorporation of marine resources slightly increased water absorption and chloride diffusion but remained within the moderate durability classification as per ASTM standards. The presence of fly ash effectively mitigated the potential adverse effects of seawater ions by refining the microstructure and reducing pore connectivity. Microstructural analysis further confirmed that the PMM mixture produced a denser hydration matrix with fewer microcracks and improved chloride binding capacity compared to the FMM mixture. Thus, controlled utilization of marine materials, particularly in combination with supplementary cementitious materials, can maintain long-term stability under marine exposure conditions.

From a sustainability standpoint, life cycle assessment (LCA) results indicated a notable reduction in environmental impacts through the substitution of freshwater and river sand with marine resources. Both PMM and FMM significantly reduced freshwater use, sand extraction, and global warming potential (GWP) relative to conventional concrete. The reductions in embodied carbon and resource depletion align with global objectives for sustainable infrastructure and coastal resilience. Consequently, the integration of marine-based materials presents a promising approach to addressing the dual challenges of material scarcity and environmental degradation in the construction sector.

RECOMMENDATION

Based on the findings, it is recommended that partial incorporation of sea water and sea sand (as in PMM) be adopted in practical applications, particularly for coastal and island regions where freshwater and natural aggregates are limited. The use of supplementary cementitious materials, such as fly ash or slag, is strongly encouraged to enhance chloride resistance and long-term durability. For reinforced concrete structures exposed to aggressive marine environments, additional protective measures — such as surface coatings, corrosion inhibitors, or controlled curing regimes — should be applied to mitigate potential reinforcement corrosion.

Further research should focus on long-term field performance monitoring, chloride binding mechanisms, and optimization of mix proportions to achieve improved microstructural refinement. Moreover, expanding life cycle assessments to include economic and social dimensions will provide a more holistic understanding of the sustainability potential of marine concrete. The combination of environmental compatibility, local material utilization, and acceptable durability performance underscores the feasibility of marine concrete as a next-generation sustainable material for resilient coastal infrastructure.

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