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The Effects of Salt Water on Concrete: A Case Study of the Atlantic Ocean

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Abstract: *This study investigates the effects of saltwater exposure on the compressive strength and durability of concrete, particularly in marine environments. Concrete specimens prepared with both fresh and saltwater in a 1:2:4 mix using a water-cement ratio of 0.5 and were tested at 7, 21, and 28 days. Samples were cured in water tanks at room temperature for 28 days. Compressive strength tests were conducted using a 2000 kN universal testing machine according to BS EN 12390-3:2019. Microscopic analysis revealed microstructural degradation such as salt crystal deposits and microcracks. Three cubes per sample were cast and the average values gotten. Microscopic analysis highlighted saltwater's impact on the concrete's microstructure. Concrete cubes were cast and cured under different water conditions, including freshwater, saltwater and Sodium Chloride (NaCl) solutions, with compressive strength tested at 7, 21, and 28 days. This process provided comparative insights into the effects of chloride and sulfate ions on the structural performance and durability of concrete. Results showed that exposure of concrete to saltwater reduced compressive strength, facilitating chloride ingress and accelerating reinforcement corrosion. Microstructural analysis identified salt crystals and microcracks as key contributors to degradation, highlighting the detrimental long-term effects on concrete durability. The results obtained from the experiment also highlight the influence of different curing environments on concrete compressive strength. Concrete cast and cured in fresh water displayed consistent strength development, reaching 25.12 N/mm² at 28 days. In contrast, concrete cast using salt water and cured in fresh water showed lower strength but reached 20.46 N/mm² at 28 days. Concrete cast in fresh water and cured in seawater demonstrated the highest strength at 28 days (26.63 N/mm²), suggesting a potential enhancement in curing efficiency. However, samples cast in fresh water and cured with NaCl had a lower strength of 22.68 N/mm².*

Keywords: *Compressive strength, concrete curing, fresh water, salt water.*

1. INTRODUCTION

Concrete is a mixture of aggregates (coarse and fine), water, binder, usually Portland cement, and a small quantity of air bubbles that are incorporated and stabilized into the cement matrix [1]. When Portland cement is hydrated, it forms cement paste, which hardens and binds aggregate into a solid mass when combined with aggregate. These constituent ingredients are aggregate to which the hardened cement binds to varying degrees and a hardened binding medium or matrix is created by a chemical reaction between cement and water [2]. The concrete mix, the curing process, the ratio of water to cement, the characteristics of the aggregates, the type of cement, etc., all influence concrete strength. The ability of concrete to withstand environmental influences and effects without compromising its intended purpose is termed durability [3].

Knowing the characteristics of coastal structures like jetties, buck heads, sea walls, revetment, oil platforms, wharves, etc. that come into contact with seawater (salt water) has become more important over the years, as these structures typically fulfil their intended functions during this time. It takes extensive study to determine the characteristics of concrete constructions, such as their strength, resilience to thawing and frost, stability, etc. When building a structure in salt water or casting or curing it in seawater, the impact of seawater on concrete has continued to be a significant issue. [4] asserts that the presence of sodium chloride in seawater accelerates the concrete's other chemicals' breakdown. The Primary chemical in seawater that reacts with concrete is magnesium sulfate ($MgSO_4$). This attack occurs through crystallization. It has been shown that sulphate attack in concrete can be caused by potassium and magnesium sulphates (K_2SO_4 & $MgSO_4$) found in seawater. This occurs through an initial reaction with the calcium hydroxide ($CaOH_2$) found in the set cement, followed by the hydration of Tri calcium silicate (C_3S) and Di calcium silicate (C_2S). When Portland cement is combined with water, the cement's constituents react to generate a cementing medium, which is used depending on the thickness of the building to be built. This paste thoroughly surrounds and coats every sand and coarse aggregate particle in correctly mixed concrete, filling up any gaps between the particles. The aggregates are bound together into a solid mass by the cement when it cures and hardens [5]. Normal conditions cause concrete to get stronger with age. It takes time for the cement and water to undergo chemical reactions that harden the components and bind the aggregates together. First, the reactions happen very quickly, and then they continue slowly over a long time [6].

Since structures made of concrete are often exposed to harsh environmental conditions, particularly in coastal areas where saltwater exposure is common as saltwater contains chloride ions which can penetrate concrete, potentially leading to deterioration and structural damage over time, this research aims to address the impact of saltwater exposure on the properties and performance of concrete structures. Specifically, the study seeks to investigate how saltwater affects the strength, durability, and overall integrity of concrete by evaluating the impact of saltwater exposure on the compressive strength of concrete over time, assessing the impact of salt water on the workability of concrete. The significance of this study lies in its potential contribution to the understanding of how salt water affects the structural integrity of concrete [7]. As concrete is widely used in coastal and marine environments, where exposure to salt water is common, understanding these effects is critical for the design and maintenance of durable infrastructure. By focusing on the curing process in different water environments, this study provides insights into the challenges posed by salt water exposure. The findings could inform best practices in construction, particularly in coastal areas, helping to improve the longevity and safety of concrete structures.

2. LITERATURE REVIEW

Seawater (Saltwater) is water from the earth's oceans and seas, characterized by its high salinity. It contains dissolved salts, primarily sodium chloride (NaCl), along with other minerals and compounds such as magnesium, calcium, and potassium. With a total salinity of roughly 3.5% (NaCl making up 78% of the dissolved solids and $MgCl_2$ and $MgSO_4$ making up 15%), seawater has a slightly higher early strength but a lower long-term strength. Sea water (SW) is a complex mixture of various salts that includes organic matter that is decomposing, suspended sediment, dissolved gasses, and living things. The main chemical components of seawater are potassium, sodium, magnesium, calcium, and chloride ions. Seawater, especially water with high chloride concentrations, frequently results in surface efflorescence and ongoing dampness. For this reason, such water should not be used in areas where plaster finishing is required or where aesthetics is crucial. Seawater has a pH that ranges from 7.4 to 8.4. Below a pH of 11, the reinforcing steel starts to corrode. Thus, cement needs to provide alkalinity when concrete is exposed to extremely harsh environments [8]. [9] opined that seawater has trace amounts of sodium and potassium salts that can react with aggregates. Consequently, even for Plain Cement Concrete (PCC), if aggregates are known to be possibly alkali reactive, saltwater should not be used. It has been noted that while using seawater when mixing concrete may occasionally cause reinforcement to corrode, it does not significantly impair the strength of the material. Adding seawater to mass or unreinforced concrete can accelerate the development of early strength due to the chemical influence of chlorides on hydration. However, it typically reduces the concrete's 28-day compressive strength by approximately 10 to 15 percent [10]. According to [1] concrete structures exposed to harsh marine environments may undergo deterioration through three main mechanisms; physical, such as freezing and thawing, wetting and drying, and abrasion; chemical attack and chloride induced corrosion.

Numerous comprehensive reviews on the subject, such as those by Mehta in [11 - 14], have contributed significantly to the understanding of the mechanisms of chemical attack and factors influencing the corrosion of steel-reinforced concrete structures in marine environments. Commercial specifications for concrete weight coatings used in submerged natural gas pipelines often prescribe the use of ASTM C150 Type II Portland cement with a maximum tricalcium aluminate (C_3A) content of 8%. This specification is typically aimed at preventing or minimizing sulphate attack on the concrete weight coating. Seawater, containing approximately 2.71% sulphate (SO_4) according to [15] is classified as a "slightly aggressive chemical environment" in [16].

Salt water and fresh water differ primarily in their salinity, composition, and applications. Salt water, found in oceans and seas, contains high levels of dissolved salts, predominantly sodium chloride, with an average salinity of 35 parts per thousand (ppt). Sea water typically has a salinity level of around 3.5%, with approximately 78% being sodium chloride, and 15% composed of chloride and sulphate of magnesium. It also contains small amounts of sodium and potassium salts. These salts can react with reactive aggregates similar to the alkaline nature of cement [21]. In contrast, fresh water, sourced from rivers, lakes, and glaciers, has a salinity of less than 0.5 ppt, making it essential for human consumption, agriculture, and industrial processes. While salt water supports marine ecosystems like coral reefs and salt-tolerant organisms, fresh water sustains terrestrial life and is vital for maintaining biodiversity.

In construction, fresh water is preferred for concrete production due to its purity, which ensures better strength and durability by avoiding issues like reinforcement corrosion caused by the chlorides in salt water. From a resource perspective, salt water constitutes 97% of Earth's water supply, requiring desalination for human use, while fresh water is only 3%, with less than 1% readily accessible. These distinctions highlight the ecological and functional roles each type of water plays, underscoring the need for sustainable management of fresh water resources [22]. Certain specifications stipulate that if water is not sourced from a proven satisfactory source, the strength of concrete or mortar made with questionable water should be compared with a similar mix using pure water [23]. Some specifications allow water for concrete if its pH value falls between 6-8 and is free from organic matter. However, instead of solely relying on pH value and other chemical composition measures, the most effective approach to determine water suitability is to make concrete with the water in question and compare the compressive strength of the concrete cubes at 7 and 28 days with companion cubes made using distilled water [24]. If the compressive strength is up to 90% of the strength achieved with distilled water, the water source can be deemed acceptable [8].

The chemical process involving the reaction between cement and water is known as the hydration of cement. The chemistry of concrete is fundamentally centred on this reaction. During hydration, specific products are formed, and these products are significant due to their cementing or adhesive properties. The quality, quantity, continuity, stability, and rate of formation of these hydration products are crucial factors. When anhydrous cement compounds are mixed with water, they undergo a reaction with each other, resulting in the formation of hydrated compounds with very low solubility. The hydration of cement can be conceptualized in two ways. The first mechanism is the "through solution," where cement compounds dissolve, producing a super-saturated solution from which various hydrated products precipitate. The second possibility involves water attacking cement compounds in the solid state, transforming the compounds into hydrated products. This transformation starts from the surface and progresses to the interior of the compounds over time [25].

The primary mineral phases in Portland cement, listed approximately in descending order of mass, include tricalcium silicate ($3CaO.SiO_2$ or C_3S), dicalcium silicate ($2CaO.SiO_2$ or C_2S), tricalcium aluminate ($3CaO.Al_2O_3$ or C_3), tetracalcium aluminoferrite ($4CaO.Al_2O_3.Fe_2O_3$ or C_4AF), calcium sulphate hemi- and dihydrate ($CaSO_4.0.5H_2O$, $CaSO_4.2H_20$), periclase (MgO), and calcium oxide (CaO) [20]. Typically, around 3 - 6% gypsum is added to regulate the hydration rate of the most reactive phase C_3A.

During the hydration of Portland cement, the earliest phases formed are calcium hydroxide (from the residual CaO in the clinker) and ettringite ($C_3A.3CaSO_4.32H_20$). As a less than stoichiometric amount of sulphate is added for the reaction with C_3A, a second phase called monosulphate ($C_3A.CaSO_4.12H_20$) begins to form after several days, leading to a concurrent reduction in ettringite content. The rate of these reactions is influenced by the amount of sulphate and the reactivity of the C_3A; the cubic form of C_3A is more reactive than the orthorhombic form [26]. Studies carried out to assess the impact of saltwater (seawater) on the compressive strength of concrete, revealed that seawater comprised the following relative compositions, presented as percentages by mass of dissolved salts: 78% NaCl, 10.5% MgCl, 5% $MgSO_4$, 3.9% $CaSO_4$, 2.3% K_2SO_4, and 0.3% NaCl. As per Bela (1989), NaCl and MgCl accounted for 88.5% of the total dissolved salts. The conclusion drawn by was that seawater positively influenced the compressive strength of concrete, regardless of the methods used. This effect was attributed to the action of crystal sulphate salts (K_2SO_4 and $MgSO_4$) on the calcium hydroxide ($CaOH_2$) produced during the hydration of cement constituents, namely C_2S and C_3S. It was emphasized that NaCl and other dissolved salts remained inert in the chemical reactions [8. 4] noted that the presence of sodium chloride in soft water accelerates the attack on other compounds in concrete.

Curing is the process of maintaining a satisfactory moisture content and favorable temperature in concrete immediately after placement, allowing the continued hydration of cement until the desired properties are sufficiently developed. As the demand for high-quality concrete increases, curing has gained importance, and it is acknowledged that uninterrupted and efficient curing contributes to an all-around improvement in concrete quality. Curing is arguably the most critical aspect of micro-silica concrete, given its minimal air bleeding characteristics. When the evaporation rate from the surface exceeds the rate of water migration from the interior to the surface, plastic shrinkage occurs. In the absence of bleeding and a gradual movement of water from the interior to the surface, early curing through membrane curing becomes necessary [27].

3. MATERIALS AND METHODS

3.1 Materials Selection

The following materials were used in the experiment:

Figure 1: Sea salt

i. **Sea Salt:** The sea salt used in this research was obtained from the Atlantic Ocean at Lagos Island, a sample of sea water was taken from the Atlantic Ocean and the salt component was extracted from the water.
ii. **Coarse Aggregate:** Crushed angular stone aggregate of maximum size of 20mm was used conforming to [28] standards.
iii. **Fine Aggregate:** The fine aggregate in this experiment was sourced locally for the batching of the concrete cubes.
iv. **Cement (Ordinary Portland Cement, OPC)**
v. **Fresh Water:** The fresh water used for curing and casting of concrete were obtained from bore hole.

3.2. Methods

The method employed was carried out to know the effect of salt water on concrete and concrete cube were made, in which some of concrete cubes were cast and cured with fresh water and remaining concrete cubes were cast and cured with sea water. The concrete cube size measured 150 × 150 × 150mm in dimension. The batching of the concrete cube was carried out by weight batching. The concrete was produced using salt water and fresh water respectively. The concrete is produced using the various salt water and fresh water respectively using 1:2:4 mixing proportion. The mix ratio was proportioned for a target cube strength of 25 N/mm^2 that had a Cement content of 315 kg/m cube, fine aggregate content of 630 kg/m cube, coarse aggregate content of 1260 kg/m cube and water cement ratio of 0.58 was used. The concrete was properly mixed using the various salt water and fresh water respectively, the concrete cubes were filled in three layers and each layer compacted 35 times. The concrete cubes were demolded 24 hours after casting. The cubes mixed with fresh water, some were cured in fresh water, while others were cured in salt water. The cubes mixed with salt water were cured only in fresh water. The curing periods are set for 6, 20, and 27 days. After each curing period, tests were conducted to determine the average compressive strength using the Universal testing machine. For each of the hydration period, cubes were tested and the average compressive strength was recorded. The concrete cubes were tested in compression testing machine and the result were reported.

3.2.1 Compressive Strength of Concrete

This represents the maximum compressive load the concrete can carry per unit area. The assessment of concrete compressive strength involves breaking cylindrical concrete or concrete cube specimens in a compression testing machine. The compressive strength is computed by dividing the failure load by the cross-sectional area resisting the load and is typically reported in units of psi or MPa in SI units. Standards such as [17] prescribe the use of concrete cubes, specifically (150 x 150 x 150) mm cubes, for determining compressive strength in quality control procedures. However, (100 x 100 x 100) mm cubes are permissible as long as the maximum size of the coarse aggregate is less than 25mm [18].
The compressive strength evaluated using eqn (1):
Compressive strength (f_p) = Load (N) / Area (mm²)

$$F_{cu} = \frac{P}{A} \tag{1}$$

3.2.2. Quality Of Water for Preparing Concrete

Water plays a crucial role in concrete as it actively engages in chemical reactions with cement. Its contribution to the formation of the strength-giving cement gel underscores the importance of both the quantity and quality of water in the concrete mix. When a structure is exposed to both air and seawater, the likelihood of corrosion of the embedded steel reinforcement increases. The attack of chlorides on the steel reinforcing and salt build up are the most detrimental or harmful effects of seawater on concrete structures [19]. For example, seawater is utilized to erect structures on a Pacific Island. If proactive preventive measures are not taken, the risk of corrosion of steel reinforcing structures will increase. Preventive actions include applying a cement slurry that has been diluted with fresh water to the reinforcement steel. In practical applications, there is often meticulous control over the properties of cement and aggregates. However, the quality of water is frequently neglected. Impurities in water can alter chemical reactions and reduce the effectiveness of cement hydration. Impure water containing salts, acids, or organic matter may lead to delayed setting, decreased strength, and long-term durability issues in the concrete mix.

3.2.3. Effect of Water Impurities on Properties of Concrete

Excessive impurities in mixing water can have detrimental effects on the strength of concrete, leading to various issues such as efflorescence (deposits of white salt on the surface), staining, corrosion of reinforcement, volume changes, and reduced durability. It is crucial to understand the harmful impacts of water impurities on concrete and determine the permissible levels of impurity during both the mixing and curing stages. Impurities in concrete are unwanted substances that can negatively affect the quality, strength, durability, and overall performance of the concrete. These impurities can come from various sources such as raw materials, water, aggregates, and environmental contamination. According to [20] some common impurities found in water are:

i. Salts: High levels of chlorides, sulfates, and other salts can cause corrosion of reinforcement and other durability issues.
ii. Acids: Acidic water can attack the cement paste, leading to deterioration.
iii. Oil and Grease: These can coat the aggregates and hinder the bond between the cement paste and aggregates.
iv. Dissolved Organic Matter: Can retard the setting and hardening of concrete.

Ensuring the quality and cleanliness of all materials used in concrete production is essential for producing high-quality, durable concrete.

Specifically, carbonates and bicarbonates of sodium and potassium are known to influence the setting time of cement. Sodium carbonate, in particular, may induce rapid setting [8].

3.3. Analysis of the Water Sample

The two samples were tested to know their degree of acidity or alkalinity using the pH meter. The pH of the two samples was determined and recorded. Moreover, water analysis was used to determine the presence of anions and acid radical in the water. The Sample were (Cl, SO_4, CO_3, GCO_3, NO_3, CA_2)

3.3.1 Determination of Ions Content

The determination of ion content was carried out using spectrophotometer methods. The procedures involved preparing blank (deionized water) for the zero of the spectrophotometers. A standard was prepared (a known concentration of the specific ion) while the sample to analyse is unknown. The blank standard sample was poured into different cuvette. The blank was placed in the first cuvette compartment, followed by the standard in the next compartment and the sample was placed on the third cuvette compartment, the sulphate content was displayed in digital form and the values was recorded.

3.4 Slump Test

The slump test is a means of assessing the consistency of fresh concrete. The test is carried out in accordance with [29] testing fresh concrete using slump test. The steel slump cone is place on a solid impermeable level base and filled with the fresh concrete in three equal layers, each layer is rammed 35 times to ensure compaction. The third layer is finished off level with the top of the cone. The cone is carefully lifted up, leaving a heap of concrete that settles or slump slightly. The upturned slump cone is placed on the base to act as a reference, and the difference in the level between its top of the concrete is measured and recorded to the nearest 5mm to give the slump of the concrete. When the cone is removed, the slump may take one of these forms: True Slump, Shear Slump or Collapse Slump. In a true slump the concrete simply subsides keeping more or less to shape. In a shear slump the top portion of the concrete shear off and slips sideways. In a collapse slump the concrete collapse completely. Only true slump is of any use in the test. If a shear or collapse slump is achieved, a fresh sample should be taken and test repeated. A collapse slump will generally mean that the mix is too wet or it is a high workability mix for which the flow test is more appropriate. The slump test can be used at site to indicate the resistance to segregation. The concrete slump test is an empirical test that measure workability of fresh concrete. The test measures consistency of concrete in that specific batch. The usual slump cone having base diameter of 200mm, top diameter 100mm and height 300mm is used. The higher the flow value, the greater its ability to fill formwork under its own weight.

4. RESULTS AND DISCUSSION

4.1 Slump Test Result

This section presents the results of slump tests conducted on three distinct concrete mixes exposed to salt water. Figure 2 shows the slump test conducted on two distinct concrete mixes of which one of the mixes was exposed to salt water. The objective is to assess how salt water influences the workability and performance of these mixes.

Figure 2: Slump Test

The results of the slump tests for the concrete mixes are summarized in Table 1 and discussed in detail below.

Table 1: Slump test results for salt and fresh water

Mix Type	Initial slump	Workability	Effects of salt water Exposure
Mix A	15mm	Moderate Workability	Salt water exposure slightly reduced the workability over time.
Mix B	25mm	Moderate Workability	Salt water exposure slightly reduced the workability over time.
Mix C	45mm	High Workability	Maintained workability better, showing superior resistance to salt water.

Mix A: The initial slump of Mix A was 15 mm, indicating moderate workability suitable for general construction purposes. This indicates that salt water exposure slightly reduced the workability of the standard concrete mix over time.

Mix B: Mix B exhibited an initial slump of 25 mm, reflecting moderate workability suitable for general construction purposes. This indicates that salt water exposure slightly reduced the workability of the standard concrete mix over time.

Mix C: The initial slump of Mix C was 45 mm, the highest among the three mixes, due to the use of salt water. The high-performance concrete mix maintained its workability better than the other mixes, indicating superior resistance to the effects of salt water.

The slump test results indicate that salt water exposure leads to a gradual reduction in the workability of concrete mixes. However, the extent of this reduction varies depending on the mix composition. The use of supplementary cementitious materials, such as fly ash and silica fume, enhances the concrete's microstructure and reduces its permeability, thereby mitigating the adverse effects of salt water. These materials improve the overall durability and performance of concrete in saline environments.

The slump test results highlight the importance of mix design in determining the workability and durability of concrete exposed to salt water. High-performance concrete mixes with supplementary cementitious materials exhibit better resistance to the detrimental effects of salt water, maintaining higher workability over time. These findings underscore the necessity of selecting appropriate concrete mix designs for structures in marine or coastal areas to ensure long-term performance and structural integrity [1].

4.2 Sea Water Analysis Results

Sea water used for casting was collected from the Atlantic Ocean for analysis before the beginning of laboratory work and after the completion of the laboratory work and the result of the analysis were presented in Table 2 and 3.

Table 2: Results of Seawater Analysis

Element	Salt water content (g/L)
Chlorides	480
Sulphate	720
Nitrate	410
Calcium ion	420
Magnesium	120
Carbonate	350
Potassium	310

Table 2 summarizes the concentrations of various elements in seawater, measured in grams per liter (g/L), emphasizing the intricate chemical composition of seawater. Each element contributes uniquely to its overall chemical profile.

Table 3: Percentage Compositions By Mass Of Dissolved Compounds In Sea Salt

Compound	Sea Salt (g/L)
NaCl	64.6
MgCl2	3.2
CaSo4	2.7
K2So4	2.7
MgSo4	2.4

Table 3 highlights the percentage compositions by mass of dissolved compounds in seawater, focusing on the primary constituents of sea salt. Sodium chloride dominates, alongside notable contributions from other compounds like magnesium chloride and calcium sulfate, reflecting seawater's complex chemical makeup.

4.3 Results of Concrete Compressive Strength

Concrete cubes cast in wooden molds were cured in fresh water, NaCl solutions, and seawater, then crushed at 7, 21, and 28 days of curing. Results were tabulated, and crack patterns were observed as shown in Figure 3.3and photographed. Notable findings included salt deposits on the surfaces of seawater-cured cubes and at the bottom of the seawater curing tank.

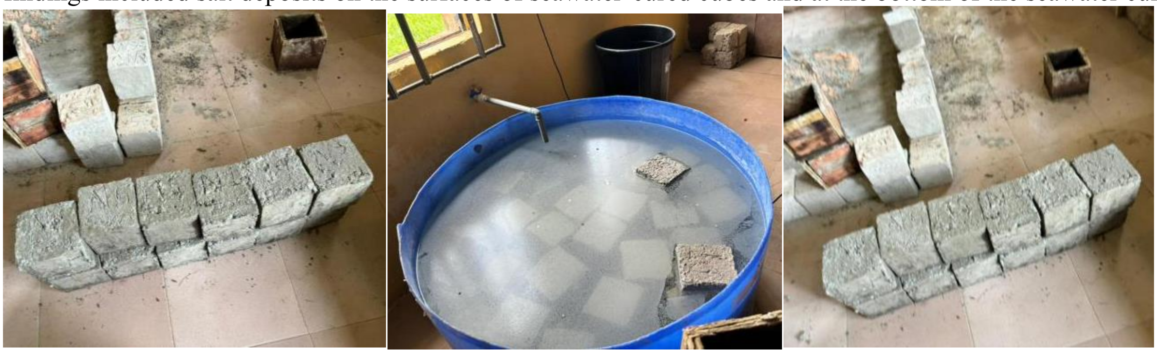

Figure 3: Cubes Cast and Cured

Table 4: Seven (7) Days Concrete Cube Weight and Applied Crushing Load

Cube Id	Cube weight (kg)	Applied load (kN)	Compressive Strength (N/mm^2)
FF	8.51 kg	490.3	21.79
NaCl	8.35 kg	472.5	21.00
Sea Salt	8.20 kg	550.4	24.46
SF	8.10 kg	380.5	16.19

Table 5: Twenty-One (21) Days Concrete Cube Weight and Applied Crushing Load

Cube Id	Cube weight (kg)	Applied load (kN)	Compressive Strength (N/mm^2)
FF	8.60 kg	542.3	24.10
NaCl	8.55 kg	490.4	21.80
Sea Salt	8.47 kg	576.4	25.62

Table 6: Twenty-Eight (28) Days Concrete Cube Weight and Applied Crushing Load

Cubs Id	Cube weight (kg)	Applied load (kN)	Compressive Strength (N/mm^2)
FF	8.61 kg	565.2	25.12
NaCl	8.63 kg	510.3	22.68
Sea Salt	8.70 kg	599.2	26.63
SF	8.60 kg	460.4	20.46

Table 7: Concrete Cube Crushing Strength (N/mm^2)

Cube Id	7 days	21 days	28 days
FF	21.79	24.10	25.12
NaCl	21.00	21.80	22.68
Sea Salt	24.46	25.62	26.63
SF	16.19	____	20.46

KEY: FF = cast in fresh water, cured in fresh water SF = cast in salt water, cured in fresh water

Figure 4: Compressive strength test

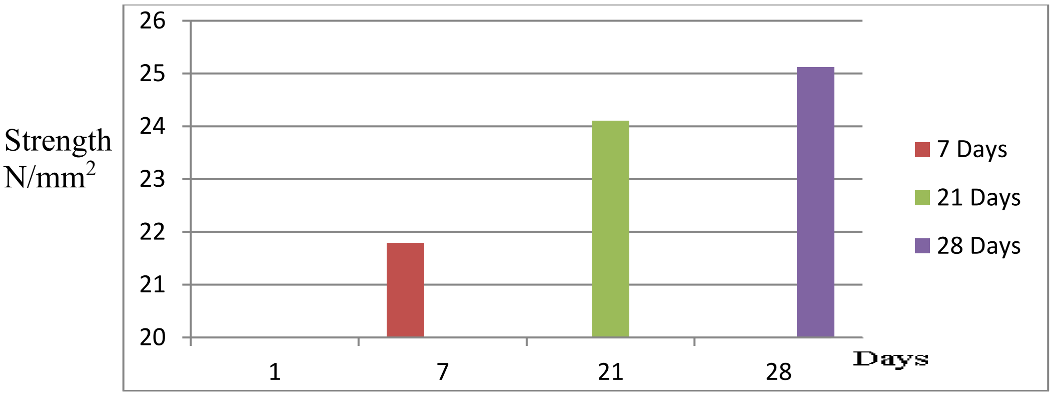

Figure 5: Compressive Strength of Fresh Water Cube

Concrete cast in Fresh Water and Cured in Fresh Water in Figure 5. This condition represents the most standard and ideal scenario for concrete curing. The compressive strengths are quite consistent, showing that curing in fresh water after casting in fresh water maintains the concrete's integrity. This indicates that the concrete maintained good hydration, which is essential for developing strength.

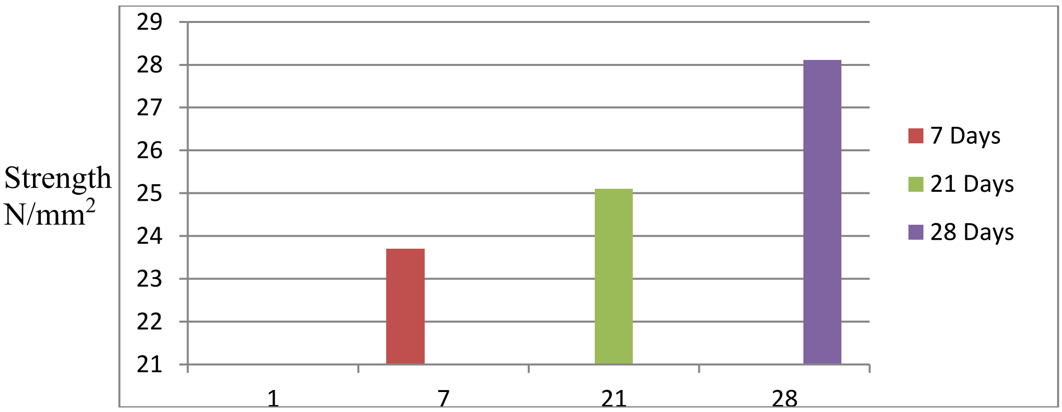

Figure 6: Compressive Strength of Sea Salt Water Cube

Concrete cast in Fresh Water and Cured in Sea Salt Solution is shown in Figure 6. This condition shows a slight improvement in compressive strength compared to the NaCl-cured & Fresh water-cured concrete. Sea salt contains a more complex mix of salts compared to NaCl alone, including magnesium and calcium, which may lead to better strength retention. It suggests that sea salt curing, though still involving salts, may help in densifying the concrete's surface slightly more than NaCl. However, long-term exposure to seawater may still result in gradual degradation due to chloride-induced corrosion.

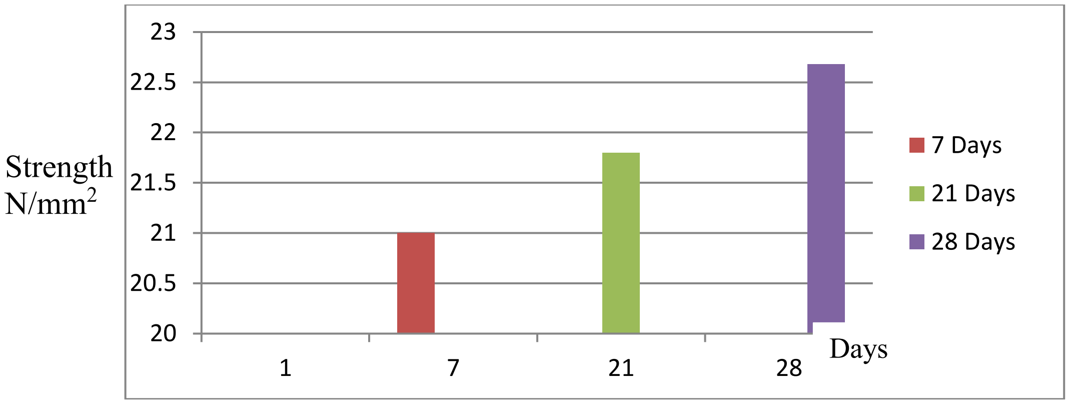

Figure 7: Compressive Strength of NaCl water Cube

Concrete cast in Fresh Water and Cured in NaCl (Sodium Chloride Solution) as shown in Figure 7. Concrete cast in fresh water and cured in NaCl solution shows a slight decrease in compressive strength compared to the first condition. Sodium chloride (NaCl) tends to increase the porosity of concrete, leading to a reduction in strength. While the decrease is not drastic, it suggests that saltwater curing weakens the concrete, likely due to chloride penetration, which can disrupt the hydration process and cause internal cracking.

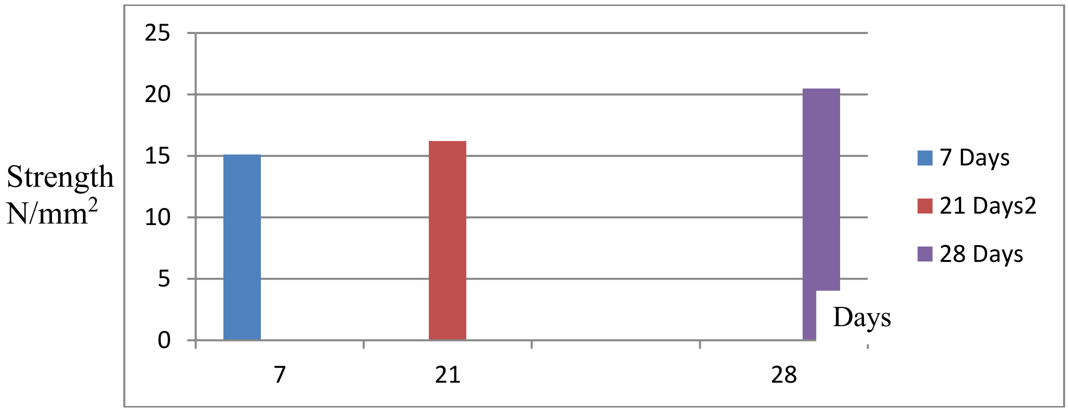

Figure 8: Compressive Strength of Cube cast in salt water and cured in fresh water

Concrete cast in Sea Water and Cured in Fresh Water shown in figure 8. The results for concrete cast in seawater and cured in fresh water show the lowest compressive strengths among all conditions. The seawater casting process introduces a significant amount of chlorides and sulfates into the mix, which negatively impacts the hydration process. Despite curing in fresh water, the initial contamination from seawater casting seems to have reduced the concrete's overall strength, possibly due to the presence of salts and harmful ions that lead to internal cracking and void formation during hydration. Concrete cast in seawater and cured in fresh water shows the weakest compressive strength due to the detrimental effects of chloride and sulfate ions introduced during casting. These salts disrupt hydration, create micro-voids, and introduce internal stresses that permanently weaken the material. Even fresh water curing cannot reverse the damage caused by the initial seawater exposure, resulting in high porosity, reduced structural integrity, and increased vulnerability to degradation. Chlorides exacerbate the problem by accelerating steel reinforcement corrosion, further reducing the concrete's strength and durability and increasing the risk of long-term structural failure.

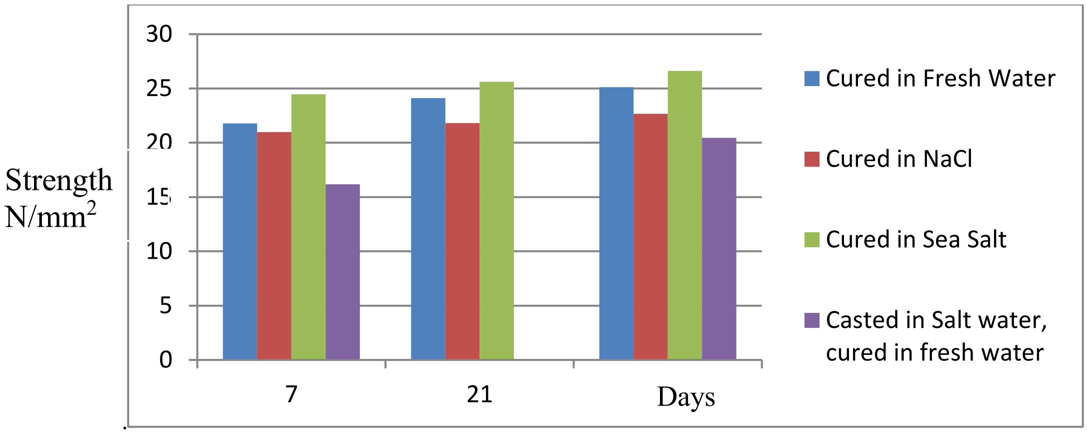

Figure 9: Average Compressive Strength of Concrete Cube at 7, 21 and 28 Days, Cast and Cured with Fresh Water and Salt water

4.4. Discussion of Results

The experimental results demonstrated the significant influence of water quality and curing environment on the compressive strength and workability of concrete. The slump test values for the three mixes revealed that salt water reduced workability compared to fresh water mixes. Mix A and Mix B, which initially recorded slumps of 15 mm and 25 mm respectively, showed moderate workability but a gradual decline when exposed to salt water. In contrast, Mix C achieved a higher slump of 45 mm and maintained superior resistance to salt water effects, suggesting that mix composition and supplementary cementitious materials play a critical role in maintaining consistency and performance in saline environments [1, 5, 7].

The seawater analysis confirmed the presence of high chloride (480 g/L) and sulphate (720 g/L) concentrations, alongside other aggressive ions such as magnesium and calcium (Table 2). These results are consistent with previous findings that chloride and sulphate ions penetrate concrete, disrupt hydration, and contribute to reinforcement corrosion and long-term deterioration [4, 8, 19]. The dominant compound identified, sodium chloride (64.6 g/L), has been widely reported as the primary factor accelerating deterioration in marine concrete structures [21, 24].

In terms of compressive strength, concrete cubes cast and cured in fresh water achieved the highest and most consistent strength development, reaching 25.12 N/mm² at 28 days (Table 6). This aligns with established knowledge that fresh water curing optimizes hydration and minimizes ion ingress [1, 2]. Concrete cast in fresh water but cured in seawater showed slightly higher strength values at 28 days (26.63 N/mm²), possibly due to surface densification from salt crystallization, though this effect may not translate into long-term durability [9, 23]. Conversely, specimens cured in NaCl solutions recorded a reduced 28-day strength of 22.68 N/mm², confirming that chloride-rich environments increase porosity and microcracking, thus lowering mechanical strength [19, 25].

The most pronounced deterioration was observed in samples cast in seawater and cured in fresh water, which reached only 20.46 N/mm² at 28 days. This condition introduced salts directly into the mix, disrupting the hydration of C_2S and C_3S phases, leading to weaker cement paste and poor bond formation with aggregates [6,20]. These findings align with earlier reports that seawater mixing reduces compressive strength by 10–20% compared to fresh water mixes [3, 10, 26]. The microstructural analysis also confirmed the presence of salt deposits and microcracks, which compromise durability and accelerate chloride-induced reinforcement corrosion [22, 27].

Overall, the numerical results highlight the detrimental effects of salt water on both fresh and hardened concrete properties. While short-term strength gains were observed in seawater-cured specimens, the long-term implications point to reduced durability due to chloride penetration and sulphate attack [11–14]. The results support earlier conclusions that fresh water remains the optimal medium for both casting and curing, while the use of seawater should be avoided in reinforced concrete unless protective measures such as polymer admixtures or supplementary cementitious materials are employed [16, 19, 27].

5. CONCLUSION

The study established that saltwater exposure significantly reduces the compressive strength of concrete over time. When samples were cast with saltwater, the 28-day compressive strength declined by about 18.6% compared to those cast and cured in fresh water. This reduction is attributed to the penetration of chloride ions, which accelerate reinforcement corrosion and disrupt the bond between cement paste and aggregates, thereby weakening the structural matrix. Saltwater also reduced the workability of concrete by accelerating hydration, producing a stiffer mix that complicates handling and placement unless corrective measures such as admixture incorporation are applied. The results further emphasized the importance of wet curing in mitigating early-age shrinkage and cracking, as it facilitates the development of a denser, less permeable matrix with improved resistance to chloride ingress. Overall, the findings highlight the vulnerability of concrete structures in marine and coastal environments and reinforce the necessity of adopting proper curing practices, protective measures, and advanced materials to enhance durability. The study recommends further research on long-term performance, including sulfate attack and reinforcement corrosion, to provide a deeper understanding of concrete behavior under prolonged saltwater exposure.

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Conflicts of Interest
The authors declare no conflicts of interest regarding this study.

Author Contributions
Daniel Ogheneochuko contributed to the study design, data collection, statistical analysis, and manuscript drafting, provided guidance on study design, supervised the laboratory work, contributed to data interpretation, and critically revised the manuscript for important intellectual content. Nelson Aboleje carried out the laboratory work and analysis.

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