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Sea Water Effects on the Mechanical Strength in Concrete on Exposure to Environmental Changes and During Curing

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Abstract: ***This paper investigates the effects of sea water on the mechanical strength of concrete through experimentation. This experimental research provides a guideline of the diverse ways in which sea water affects concrete and the dependency of the factors involved. The research investigates the effects of Sea water salts like sodium chloride as a curing method at different concentration on the mechanical strength of solid concrete cubes and specimens. Concrete cubes containing immersed in seawater show an early increase in compressive strengths in 3 to 7 days with control concrete cubes at 28 days which contains sodium chloride casted and cured in seawater recorded slightly higher strength compared to control cubes.The paper examined the mechanical properties of solid concrete in exposure to sea water as as well as fresh water under some environmental conditions. The results indicate that the flexural, compressive plus split tensile strength of the concrete casted as well as cured in sea waters was higher in relation to that of concrete specimens casted as well as cured in distilled fresh H_2O. The comparative difference however was not significant. Theresults also show that sea water negatively affect durability of concrete under various environmental conditions.***

Keywords: effect of sea water on concrete, effect of SodiumChloride on concrete, mechanical properties of concrete, Sodium Chloride in sea water

1. Introduction

Salts contained in sea water are mainly Chloride and Sulphate compounds. Ions in sea water participate in chemical reactions with the components of the concrete, leading to the formation of complex salts which cause pressure in the concrete microstructure, leaching of the concrete components which compromises the concrete structure and corrosion of the reinforcement steel which reduces the load weight of the solid concrete structure.[1] The effect of salt compound reactions with concrete components results in deterioration and loss of mechanical strength in concrete.

Action of sea water on concrete rises with a rise in concentration of aggressive within the sea water; however, it is also dependent on temperature, pressure, material and concrete mix design of the structure and relative humidity. Increased sea water action is observed under high temperatures and pressure, porous concrete structure also encourages capillary action and the accumulation of deleterious material and regular fluctuations in the relative humidity [2].

This paper deals with the comparative effects of salt water as well as fresh water on the mechanical force on concrete. It includes twenty experiments to compare the effects of sea water as well as fresh water on concrete during casting and curing, and under immersion and exposure to different environmental conditions.

2. Materials and specimens mix design

Forty cylindrical concrete specimens of size 10 x 22 cm were cast as per ASTM 192 standard practices in the making as well as curing concrete specimens to be tested in the laboratory. Ordinary Portland cement (OPC), fine aggregates and coarse aggregates were mixed in the ratio 1:2:3 to form the concrete beams. Crushed granite stones with diameter ranging between 3 mm and 20 mm were used as granular aggregates while natural washed sand passed through a 4.5 mm sieve was used as the fine aggregate. Ordinary portable water without any suspensions or chemical impurities was used in both casting and curing some of the specimens. The salt water solution with an average salinity of 35 grams per litter was used.

Testing of cement, fine and course aggregates was done and the properties of the materials recorded in tables 1, 2 and 3 below:

Table 1: Cement ingredients used

Characteristics	Obtained Values
Fineness (%)	5.4
Standard Consistency (%)	28
Initial Time Setting in minutes	38
Final Time Setting in minutes	550

Table 2: Properties of fine aggregates used

Characteristics	Obtained Values
Type	Natural washed sand
Specific Gravity	3.0
Water absorption (%)	0.75

Table 3: Properties of the rough aggregates used

Characteristics	Obtained Values
Crushing value test (%)	36
Specific Gravity	3.3
Water absorption (%)	1.1

The water cement ratio for all specimens was 0.45, while fine aggregates and coarse aggregates formed 31% and 46% of specimens respectively.

The salt compound composition of the salt solution used as sea water within the experiments is as provided in table 4 below:

Table 4: The salt composition of salt water used

Salt compound	Composition (grams per litre)
Sodium Chloride	27.3
Magnesium Chloride	3.675
Magnesium Sulphate	1.75
Calcium Sulphate	1.365
Potassium Sulphate	0.91

3. Specimens preparation and preliminary tests

Cement and sand used in the experiment were mixed until they were thoroughly blended before the addition of coarse aggregates for approximately 15 minutes. Crushed stones were then added and mixed till uniform distribution was established. Further machine mixing was done for approximately 25 minutes till homogeneity and consistency in the concrete paste was established. Specimens' preparation was conducted in a moist room as per ASTM 511standards on moist cabinets, mixing rooms, water storage tanks as well as rooms were put in use in hydraulic cement testing as well as concrete. The temperature in moist rooms and missing H2O were maintained on 20^{o}C while relative humidity was kept 95%. The internal vibration at 110 Hz and external vibration at 70 Hz were performed on the concrete paste to enable air bubbles in the paste to move to the surface.

The concrete paste was then cast in cylindrical molds for 24 hours. After de-molding, all specimens were subjected to standard wet curing for 28 days at 20^{o}C. Twenty specimens for use in investigating the effects of concrete exposure to sea water were casted in addition cured using fresh distilled water. The other twenty specimens used to investigate of the comparative effects of sea water with compressive strength of concrete specimens when in use in casting as well as curing were cast and cured in either fresh water or salt water.

After curing specimens were separated into twenty; (1) specimens to be used for investigating the effects of salts in sea waters on compressive forces when used in curing (2) specimens to be used in investigating the effects of salts in sea waters on compressive forces of solid concrete structures dipped in sea waters under different environmental conditions. Compressive, flexural and tensile strength for the specimens was measured. Initial mass of specimens was also measured; all concrete beams were air dried at 24^{o}C and relative humidity of 55% before measurement of the initial Mass.

4. Exposure conditions and experimentation procedure

Twenty experimental procedures were involved in testing the effects of sea water on concrete strength:

Experiment 1: Effect of sea water when used in casting and curing of the concrete

Ten concrete specimens were cast and cured in a pair under different casting and curing conditions. The specimens were labeled according to the preparation conditions as follows:

CS1: Casted and cured in fresh water
CS2: Casted using salt water and cured in fresh water
CS3: Casted using fresh water and cured in salt water
CS4: Casted and cured in salt water
All specimens were cured within 28 days, 20^{o} C temperature as well as 95% RH. Compressive, flexural and tensile strength tests were conducted at 7-day intervals.

Experiment 2: The Effect of sea water on concrete structures exposed to its action under cyclic environmental changes

Freeze and thaw conditions; ten specimens cast and cured in fresh water were immersed in the salt solution while ten specimens were immersed in fresh water. All specimens were exposed to twenty-eight days of 24-hour freeze and thaw cycles. A freezing chamber was used to freeze the specimens at -20^{o}C for 16 hours the specimens were then the air warmed to 24^{o}C before being immersed in 24 ^{o}C solutions for 8 hours. The specimens were then air cooled to -20^{o}C to complete one cycle. Specimens testing were conducted after 7, 14, 21 and 28 cycles.

Wet and dry conditions; twenty specimens cast and cured in fresh water were used. Twenty specimens were immersed in the salt solutions while the remaining twenty were immersed in fresh water. All specimens were exposed to wet cycles at 5^{o}C for 14 hours then air dried at 23^{o}C for 10 hours and 95% relative humidity to complete one 24-hour cycle. The specimens were subjected to 28 cycles with testing being conducted at intervals of seventy cycles and at the end of the experiment.

The concentration of the solution in two conditions was monitored after every seven days; with the solution being replaced in circumstances where there was a decline.

5. Tests and analysis procedures

Compressive, flexural and split tensile strength tests were conducted on specimens for both experiments at 7, 14, 21 and 28 days. Micro structural damage in the concrete beams was investigated using the power dispersive X-ray spectrometer analysis (SEM - EDS) as well as scanning electron microscope. Schottky field emission SEM with

3.0 NM resolution at 5 kV was used in the SEM EDS analysis. Samples from the concrete beams were dried for 24 hours at 90°C then coated with an ultra-thin layer of steel before testing.

X-ray diffraction examination also conducted on samples from specimens to identify the crystallization phases of the pore solution in the concrete. An x-ray diffractometer at 40 kV radiation and Jade 7 diffraction software were used to analyze the crystal content of the specimens' samples.

Visual inspection of specimens also conducted as well as concrete deterioration rated based on a proposed rating. Statistical analysis of the compressive strength data collected, a dynamic modulus of elasticity and correlation analysis between various variables affecting concrete in salt solutions were conducted.

Percentage mass loss during the test time intervals was measured according to the equation (1) below:

Mass loss at a time $t = (M_t - M_{t-1})/M_{t-1} * 100$ (1)

t is taken as the test period interval, M_t as the mass of the concrete beam at a time t while M_{t-1} as the mass of specimens of the previous test time period (t-1)

6. Results and discussion

Experiment one:

The flexural, compressive plus split tensile strength of the concrete casted as well as cured in sea waters was higher in relation to that of concrete specimens casted as well as cured in distilled fresh H2O. The comparative difference however was not significant. The Figures 1, 2 and 3 show the comparative differences in strength between specimens casted and cured in salt water and specimens casted as well as cured in fresh water:

Table 4: Compressive strength variations under sea water, and fresh water casting and curing in MPa (megapascals)

	7th day	14th day	21st day	28th day
CS1	13.58MPa	20.881 MPa	28.182 MPa	34.44 MPa
CS2	17.59 MPa	23.6625 MPa	29.735 MPa	34.94 MPa
CS3	14.79 MPa	22.0385 MPa	29.287 MPa	34.5 MPa
CS4	19.56 MPa	24.6675 MPa	31.775 MPa	37.01 MPa

From the above results, we realize that compressive strength of solid concrete increases as days go by. The strength increases in different conditions implying that putting aside the long-term effects, sea water is considered the best in mixing concrete ingredients and curing the structure.

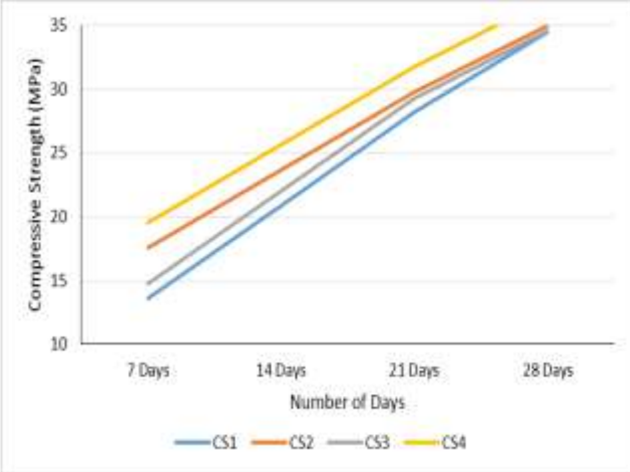

Figure 1: Compressive strength variations under sea water, and fresh water, casting and curing.

Table 4: Tensile strength variations in concrete under exposure to sea water and fresh water casting and curing

	7 Days	14 Days	21 Days	28 Days
CS1	1.258 MPa	2.0881 MPa	2.8182 MPa	3.454 MPa
CS2	1.559 MPa	2.36625 MPa	2.9735 MPa	3.484 MPa
CS3	1.379 MPa	2.20385 MPa	2.8287 MPa	3.45 MPa
CS4	1.956 MPa	2.46675 MPa	3.0775 MPa	3.711 MPa

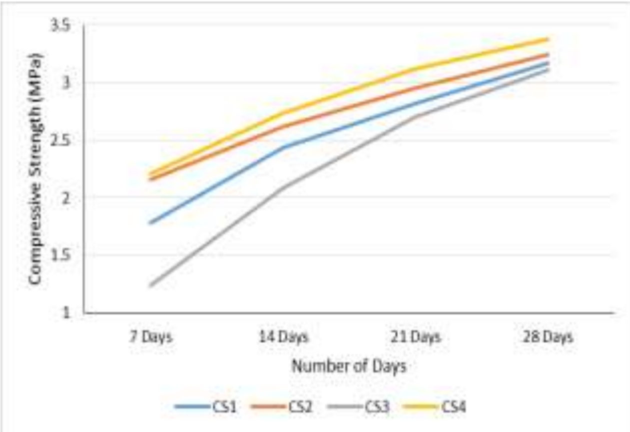

Figure 2: Tensile strength variations in concrete under exposure to sea water, and fresh water casting and curing

Table 5: Flexural strength variations in concrete under exposure to sea water and fresh water casting and curing in megapascals (MPa)

	7 Days	14 Days	21 Days	28 Days
CS1	4.9	5.2	5.5	6.1
CS2	4.7	5.01	5.24	5.6
CS3	4.1	4.6	5.03	5.53
CS4	3.5	4.2	4.8	5.53

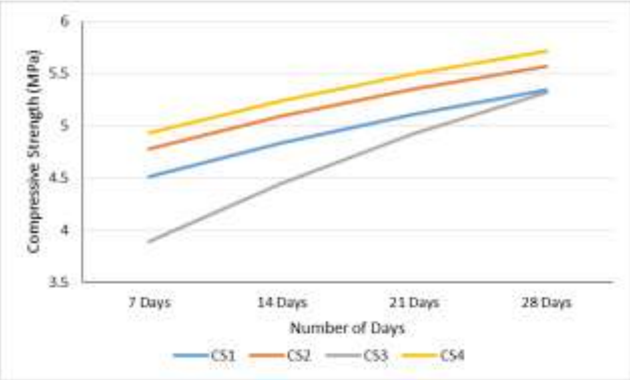

Figure 3: Flexural strength variations in concrete under exposure to sea water and fresh water, casting and curing

Experiment 2:

After 28 days under exposure to freezing and thawing conditions an extensive compressive and tensile strength reduction was recorded from the specimens immersed in salt water. Insignificant strength reduction was recorded from the specimens immersed in fresh water under the same conditions. Figure 4 below shows, the comparative variations in compressive strength between specimens immersed in salt water as well as the specimens dipped into fresh distilled water:

Table 6: Comparative effects of salt water and fresh water of compressive strength of solid concrete in freezing – thawing cycles

number of cycles	sea water	fresh water
0	34.5	34.5
7	29.325	30.36
14	24.955575	26.89896
21	21.34949441	24.22251348
28	18.29651671	22.10425468

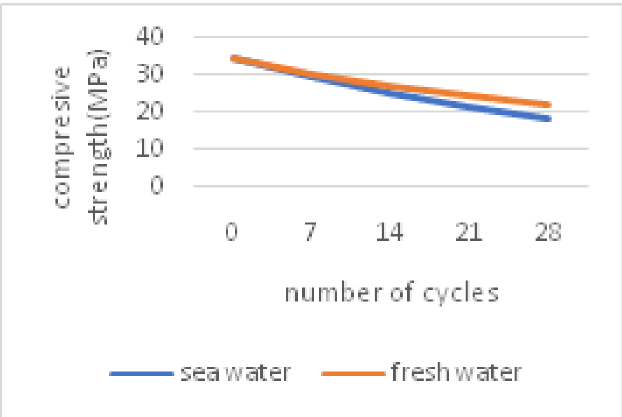

Figure 4: Comparative salt water and fresh water effects on compressive strength for solid concrete in freezing – thawing cycles

From the graph above we realize that sea water has a slight decrease of compressive strength which is insignificant. There is a strong compressive strength which reduces over time just like in fresh water.

Data collected indicates a correlation between the salt content of water and the degree of reduction in tensile strength. Specimens immersed in salt water and exposed to freeze and thaw conditions also exhibited significant tensile strength loss in relation with specimens dipped in fresh water and exposed to the same conditions. Figure 5 below shows, the comparative effects of fresh water as well as salt water to the breaking strength of solid concrete:

Table 7: Tensile strength variations in concrete immersed in fresh and salt water, under freezing and thawing cycles

number of cycles	sea water	fresh water
0	1.43	1.43
7	1.37212293	1.494957985
14	1.237938685	1.334746539
21	1.1496452	1.201278021
28	1.07988395	1.09075205

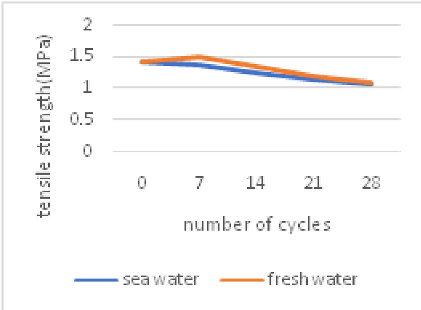

Figure 5: Tensile strength variations in concrete immersed in fresh and salt water, under freezing and thawing cycles

The effects of salts current in sea water to the compressive strength of solid concrete also exhibited under wet and dry conditions. Slight compressive strength losses were recorded in specimens' exposure to salts in sea water in relation to fresh distilled water. Figure 6 below shows, the comparative effect of fresh and salt water under exposure to wet – dry cycles:

Table 8: Compressive strength variations in concrete specimensimmersed in salt and fresh water under exposure to wet – dry cycles

Number of Cycles	fresh water	sea water
0	38.6	38.6
7	34.1119496	28.79179867
14	31.98698609	21.61296676
21	29.57196864	17.52350167
28	27.76807855	14.64456558

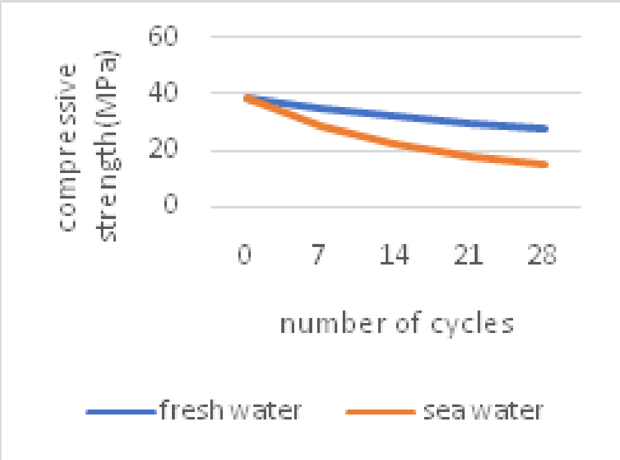

Figure 6: Compressive strength variations in concrete specimens immersed in salt and fresh water under exposure to wet – dry cycles

Insignificant tensile strength loses were exhibited in specimens exposed to fresh water; extensive strength loses however were exhibited in the specimens immersed in salt water under wet – dry cycles. Figure 7 below shows, the comparative tensile strength loses in specimens exposed to salt and fresh water under wet – dry cycles:

Table 9: Comparative tensile strength changes in specimens immersed in salt and fresh water under exposure to wet – dry cycles

number of cycles	sea water	fresh water
0	1.548076291	1.548076291
7	1.44877877	1.260867364
14	1.357258503	1.0315287
21	1.284687244	0.890668047
28	1.229315412	0.785515558

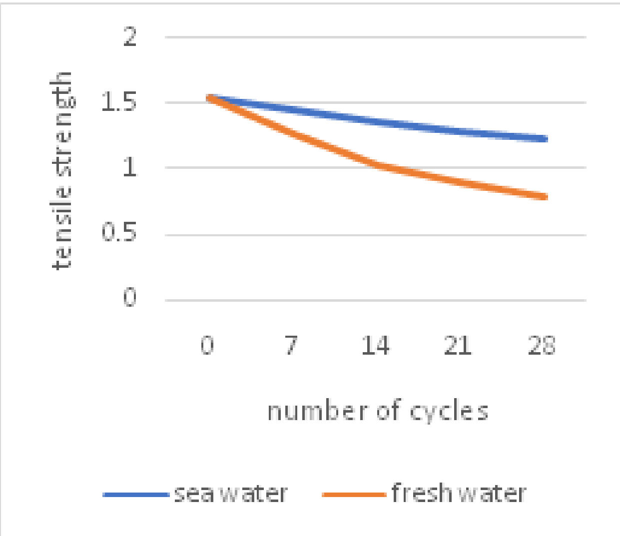

Figure 7: Comparative tensile strength changes in specimens immersed in salt and fresh water under exposure to wet – dry cycles

The impact of sea water on the mechanical force of solid concrete was also more pronounced in specimens exposed to freeze and thaw conditions as compared to those exposed to wet – dry cycles. Figure 8 below shows, comparative effects of salts in sea water when exposed to varying environmental conditions:

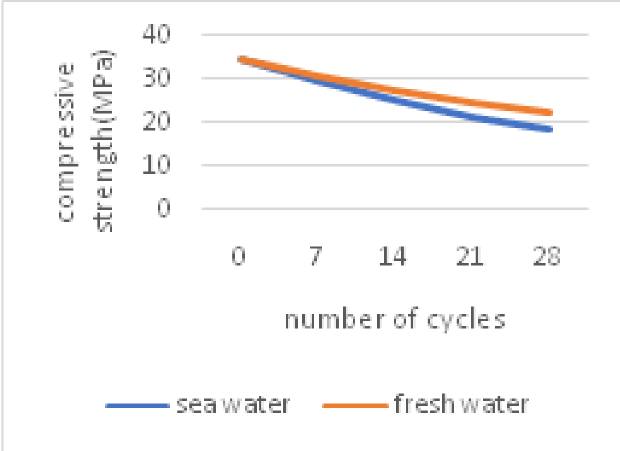

Figure 8: Comparative effects of salt water under exposure conditions to freezing – thawing cycles as well as wet–dry cycles

Physical deterioration observed in specimens immersed in salt water under freeze – thaw conditions; the extent of deterioration observed in specimens immersed in fresh water, however was insignificant.

Figures 9 and 10 shows the comparative differences in the observable effects of sea water and fresh water:

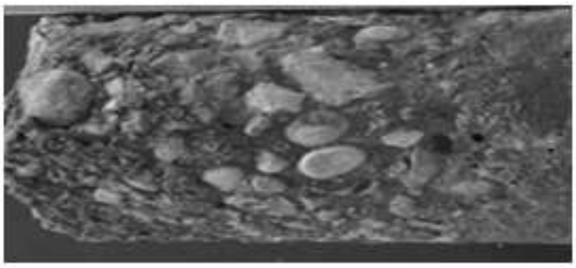

Figure 9: Specimens after 28 days of immersion in salt water under exposure to freeze – thaw cycles

Figure 10: Specimens after 28 days of immersion in fresh water under freeze and thaw conditions.

A higher deterioration in specimens immersed in salt water was also observed under exposure to wet – dry cycles as compared with specimens immersed in fresh water. Figures 11 and 12 below shows, the comparative observable effects of the sea and fresh water on concrete under wetting and drying conditions:

Figure 11: Concrete cylinder after 28 days immersion in salt water under wet – dry cycles

Figure 12: Concrete cylinder specimens after 28 days immersion in fresh water under wet – dry cycles

The effect of salt water on the specimens was also observed to vary according to environmental exposure conditions. Specimens exposed to salt water under freeze – thaw cycles exhibited higher rates of deterioration as compared to those exposed to wet – dry cycles.

Tests and analysis procedures for Sodium Chloride in sea water on the mechanical strength of concrete under various environmental conditions

Mass loss, compressive strength, tensile strength, porosity and microstructural damage tests were done at 7, 14, 21 and 28 days. Microstructural damage in the concrete beams investigation was done by using the electron microscope for scanning through the dispersing X-ray spectrometer (SEM-EDS) analysis which uses energy Yao et al [51]. A Schottky field emission SEM with 3.0 NM resolution at 5 kV was used in the SEM EDS analysis. Samples from the concrete beams were dried for 24 hours at 90^{o}C then coated with an ultra-thin layer of gold palladium before testing.

X-ray diffraction examination also done on samples from specimens to identify crystallization phases of the pore solution in the concrete. An x-ray diffractometer at 40 kV radiation and Jade 7 diffraction software were used to analyze the crystal content of the specimens' samples.

Physical inspection of specimens also conducted and concrete deterioration rated based on a proposed rating system by Yao et al [51]. Statistical analysis of the compressive strength data collected, a dynamic modulus of elasticity and correlation analysis between various variables affecting concrete in salt solutions were conducted.

Percentage mass loss during the test time intervals was measured according to the equation (19) below:

Mass loss at a time t = $(M_t - M_{t-1})/M_{t-1} *100$ (1)

Taking t as the test time interval, M_t as the mass of concrete beams at a time t while M_{t-1} as the mass of specimens of the previous test period interval (t-1)

7. Results and discussion

At 28 days significant deterioration was seen on the specimens dipped in Sodium Chloride solutions under freezing – thawing as well as wetting - drying environments. More deterioration and surface scaling was observed in concrete beams in exposure to freezing as well as thawing conditions as compared to wet as well as dry cycles. Comparatively lower scaling and deterioration was observed in specimens that were unexposed to freezing and thawing or wetting and drying conditions.

Figure 13: Concrete beam after 28th day dipping in a 2% concentrated Chloride solution with no exposure to freeze and thaw or wet and dry cycles

Figure 14: Specimens after 28th day immersion in 4% concentrated Chloride solution under exposure to wet and dry condition

Figure 15: Specimens 28th day immersion in a 4% concentrated Chloride solutions under freeze and thaw conditions

The result indicates that actions of Sodium Chlorides on solid concrete are aided via humidity and temperature changes in the concrete micro structure and hence observation of significantly higher deterioration in specimens under exposure to freezing-thawing and wet-dry conditions.

Significantly higher deterioration and surface scaling was also observed in specimens exposed to a highly concentrated solution. Figure 16 and 17 below shows, effect of increased concentration on concrete beams:

Figure 16: Specimens after 28th day of immersion in 2% concentrated Chloride Solution

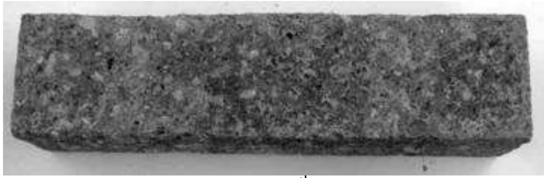

Figure 17: Specimens after 28th day of immersion in 6% concentrated Chloride solution

The effect of the Chloride ions on the specimens was also observed to increase with an increase in the porosity of the specimens. Comparatively higher deterioration was observed in specimens with an air content of 6% as compared to those with an air content of 3%. Figures 18 and 19 show the effect of increased porosity on Chloride action in specimens exposed to wet and dry cycles at 14 days:

Figure 18: Specimens with 2% air masses after 14 days of dipping within the concentrated solution

Figure 19: Specimens with 7% air masses later in 14 days of dipping in 6% concentrated solution.

Compressive strength and tensile strength data analysis indicates a correlation between exposure of the specimens to water action in freeze - thaw and wet – dry conditions and loss in concrete strength. Compressive and tensile strength loss was exhibited in all specimens; the effect however was significantly higher in specimens' exposure to freezing as well as thawing conditions due to combined physical and chemical the effects of chloride ions in the solution. Figures 20 and 21 below shows, the comparative effects of the exposure environment.

Table 10: Comparative analysis of the effect of Sodium Chloride on the compressive strength under different exposure environments, using specimens with 2% air content

2% Air			
Number of Cycles	**Freeze – Thaw**	**Wet - Dry**	**No Exposure**
0	34.5	34.5	34.5
7	27.945	28.98	30.015
14	23.19435	24.0677	26.71335
21	19.59922575	22.310253	24.4160019
28	16.81613569	20.38153163	22.9510417

Table 11: Comparative analysis of the effect of Sodium Chloride on concrete tensile strength under different exposure environments, using specimens with 2% air content

	2% Air		
N. of Cycles	Freeze – Thaw	Wet – Dry	N. Exposure
0	1.43	1.43	1.43
7	1.234792906	1.266631	1.29812979
14	1.083799111	1.144356625	1.196440468
21	0.963271002	1.054713228	1.123449179
28	0.865345597	0.990026953	1.075828211

Figure 20 Comparative analysis of the effect sodium chloride on the compressive strength under different exposure environments, using specimens with 2% air content.

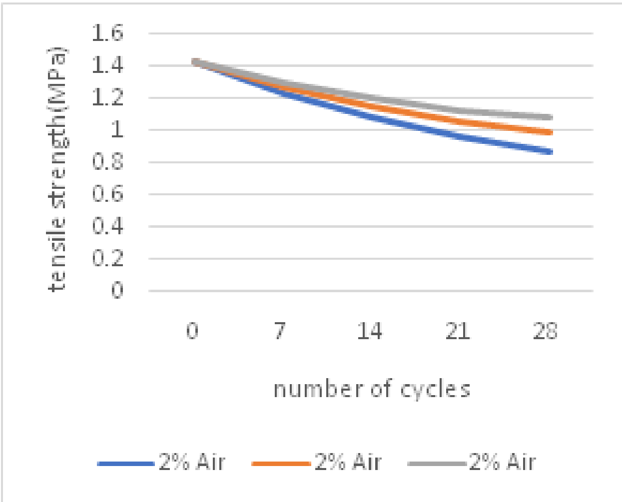

Figure 20: Comparative analysis of the effect of sodium chloride on concrete tensile strength under different exposure environments using specimens with 2% air content.

The data collected also indicates a correlation between the concentration of the solution and the losses in compressive and tensile strength in the specimens. Specimens exposed to a highly concentrated solution exhibited significantly higher strength loss rates.

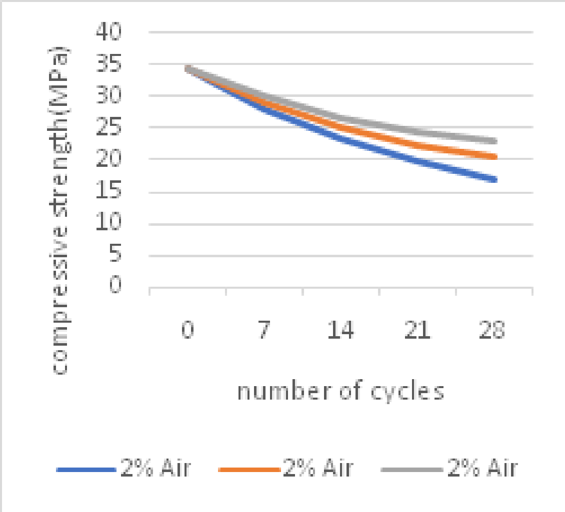

Figure 21: Comparative analysis of the effect of Sodium Chloride on the compressive strength under different exposure environments, using specimens with 2% air content

Table 12: Concentration of salt effects on compressive strength of the concrete beams

Number of Cycles	2% Concentration	6% Concentration
0	34.5	34.5
7	31.382442	32.0229
14	28.58940466	30.02
21	26.43090461	28.23
28	24.81861943	27.466

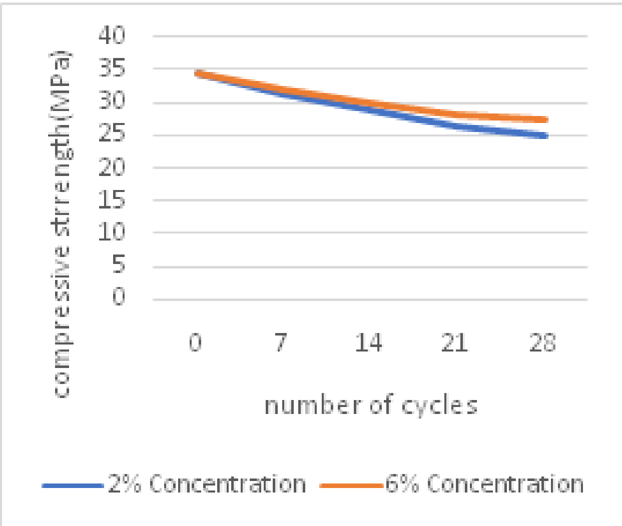

Figure 22: Concentration of salt effects on compressive strength on concrete beams

Table 13: concentration of salt effects of the tensile strength

Number of Cycles	2% Concentration	6% Concentration
0	1.431049356	1.431049356
7	1.339250942	1.358325042
14	1.254656452	1.298281078
21	1.187571223	1.243594695
28	1.136385228	1.21993878

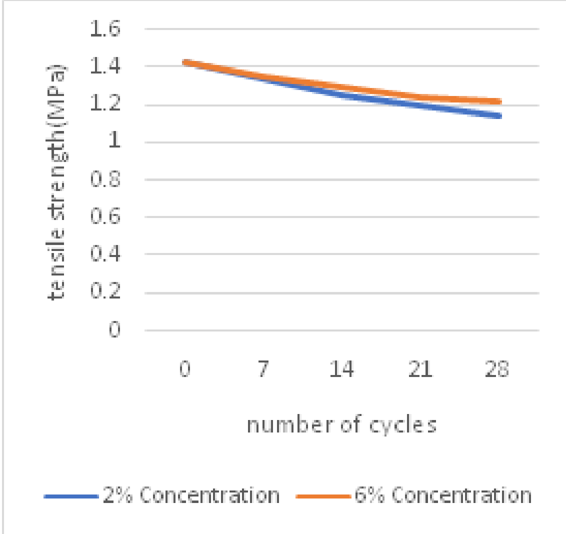

Figure 23: concentration of salt effects of the tensile strength

Correlation analysis on compressive strength tests also indicated a relationship between the rate of strength loss and the air content of the concrete specimens. Specimens with a higher air content percentage exhibited significantly higher compressive and tensile strength losses. Figure 23 below highlights the comparison of concrete air content with compressive strength loss:

Table 14: Effects of porosity on chloride action as well as compressive strength on concrete

N. of Cycles	Freeze - Thaw 2% air c	Wet - Dry 2% air	Freeze - Thaw 7% air	Wet - Dry 7% air
0	34.5	34.5	27.6	27.6
7	29.325	30.36	23.184	24.012
14	24.955575	26.89896	19.497744	21.034512
21	21.34949441	24.22251348	16.48534255	18.731232
28	18.29651671	22.10425468	13.96308514	16.905874

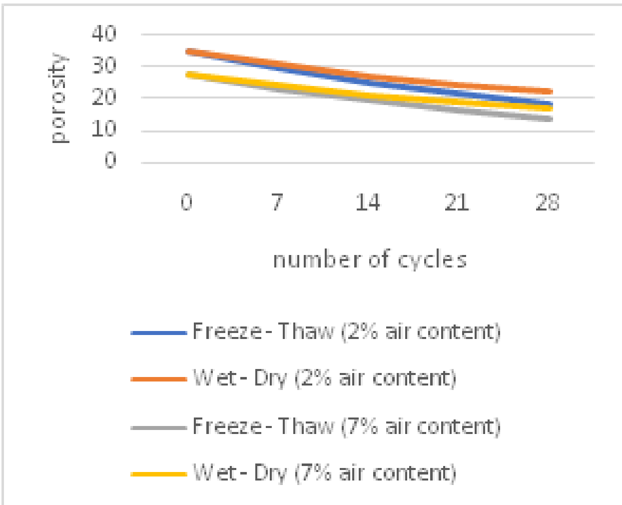

Figure 24: Effects of porosity on chloride action as well as compressive strength on concrete

8. Conclusion for effects of Sodium Chloride ions in sea water on concrete

In addition, investigation of the performance of concrete specimens with different air content immersed in 2%, 4% and 6% Sodium Chloride solutions. Investigations were done under different exposure environments with cyclic wet and dry conditions and cyclic freeze and thaw conditions being compared with normal exposure to the Sodium Chloride solution at a constant temperature as well as comparative moisture.

The conclusions from the experimental laboratory results are:

- Sodium Chloride ions led to decreased durability in concrete structures; with surface scaling, mass loss, compressive strength loss and tensile strength losses contributing to the damage. This can be attributed to the chemical as well as physical action of Sodium Chloride ions.
- Concrete structures immersed in Sodium Chloride solutions under freeze and thaw conditions exhibit comparatively higher levels of deterioration as compared to other environmental exposure conditions due to additional effects of water resulting to expansion when it freezes to form ice.
- Compressive and tensile strength loss occurs as the exposure time increase; with extensile strength loss being recorded on completion of the experiment due to the continued physical as well as the chemical attack of Sodium Chloride ions on the concrete.
- Increased concentration of the Sodium Chloride solution results in increased deterioration of concrete structure due to an increased number of free Sodium Chloride ions that attack the concrete
- Air content in concrete reduces the impact of sodium chloride attack under freeze and thaw conditions; however increased porosity in the concrete microstructure increases damage due to the accumulation of deleterious material.
- Sodium Chloride crystallizes within the concrete microstructure; exerting pressure eventually results to cracking as well as breakage of concrete.

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