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POTIENTIAL INCORPORATION OF SALINE WATER INTO PORTLAND CEMENT REINFORCED CONCRETE

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Abstract: Fresh water scarcity is one of the major concerns in the world nowadays due to amid global warming and rapid increase of population. The population is escalating significantly and is expected to reach its critical peak by 2050 leaving 2.8 billion people in 48 countries facing water scarcity. Against this background, this study investigates the potential incorporation and feasibility of replacing fresh water with seawater as mixing water as well as curing water in concrete manufacturing. To meet this objective, various mixtures were prepared with various levels of strengths while incorporating different corrosion protection measures to minimize steel corrosion. The properties of the concrete were evaluated through fresh tests as slump, unit weight, air content and temperature, mechanical properties namely compressive strength, flexural strength and bond strength were obtained and accelerated corrosion testing through impressed voltage method was carried out. A feasibility case study was conducted to quantify the cost savings resulting from replacing freshwater with seawater in mixing and curing concrete. This work achieves a better understanding of concrete behavior when seawater is incorporated. The study attempts to identify measures for careful incorporation of sea water into concrete.

1 INTRODUCTION

Fresh water stress and scarcity are major concerns in the world nowadays. The UN medium population projections of 1998 expected that that by 2050, 2.8 billion people in 48 counties will be facing water stress or scarcity conditions (Atakan et al. 2016). Nowadays, about 1.2 billion people, one fifth of the world's population, live in areas of water scarcity and 500 million people are approaching this situation (United Nations 2014). Concrete is the second most consumed material worldwide after water due to the growing trend to industrialize and urbanize countries (Atakan et al. 2016). Concrete is highly dependent on water in its formation as it is used for the hydration reaction with the cement to form the cement paste that binds the concrete mix and gives the concrete strength, hardness and durability, water is also used for concrete curing which is essential to maintain the water required for the hydration reaction with cement and prevent concrete dryness and thus its cracking. The fresh water consumed in mixing and curing concrete is non-renewable and amounts to about 2150 million to 2600 million m^3 yearly (Miller et al. 2018), the problem is even more critical in the future as studies have shown that 75% of the water demand by the concrete industry will occur in areas which are anticipated to experience water stress at the time and in 2050 it is anticipated that some countries like Brazil and India will have 80% and 90% increase in their concrete production, those and similar countries will raise the consumption of fresh water by the concrete industry to about 2300 to 2800 Km^3 (Miller et al. 2018). The usage of fresh water in concrete also causes special problems to projects in the coastal areas far away from fresh water sources since those projects use transported fresh water from far away areas which is very costly (Guo et al. 2018). Thus, to save the fresh water used in concrete mixing and curing and to save the costs of transporting them to projects, research was conducted to investigate the possibility of replacing the fresh water in concrete with seawater. Previous research aimed to understand the effect of using seawater in mixing and curing on the properties of concrete; however, the possibility of using seawater in reinforced concrete is an understudied topic. Thus, this research intends to investigate the possibility of replacing fresh water with seawater in reinforced concrete by using different corrosion protection measures to prevent or decrease steel corrosion.

2 LITERATURE REVIEW

2.1 Compressive Strength of Seawater Concrete Mix and Curing

Since different concrete grades and design mixes result in different compressive strengths, a study to investigate the compressive strength of seawater concrete mix is made. The used concrete grade is M30 and the number of days is limited to 28 days for this study. Generally, the use of seawater in mixing and curing result in early gain in strength but ultimate decrease in strength afterwards contributing around 15% of loss after 90 days. A decrease in loss reaching 7% is shown for freshwater mix and seawater curing. A decrease in strength was also attributed to the higher concrete grades for seawater mixing and curing (Guo et al. ,2018). This may be due to lower cementitious cover surrounding the aggregates.

2.2 The Effect of Cement Types in Seawater Mixing and Curing

The effect of chloride ingress can be reduced by using the appropriate type of cement in which the C_3A component reacts with the chlorides to form calcium chloro aluminates. Sulphate resisting cement has lower amounts of C_3A (cement type V) and thus less chloride binding. The literature showed that pure C_3A binded chlorides the most. The use of silica fume decreases alkalinity due to the presence of silicon and increases the dissolution of calcium chloro aluminates. For lower water to cement ratios, there was a significant reduction in chloride binding for the same dosage of silica fumes (Yetterdal, 2014). The main factors attributing to the effectiveness of chloride binding are the water to cement ratio and the type of cement where high w/c ratios increase chloride binding and type I cement or Ordinary Portland cement is more effective than any other cement type for seawater mixing or curing.

2.3 Bonding Test

Bonding tests are done to investigate one of the many causes of failures of reinforced concrete structures particularly under flexure, tensile and compressive loading. The values obtained for flexure under center point load testing is explained by the bonding resistance values obtained. Failure of flexure loading is usually caused by decreased durability which leads to the ingress of moisture and oxygen which initiate corrosion and the other main culprit is the bonding. As for the smooth steel bar, friction is not a primary factor which leads to the conclusion that there exists a chemical binding between the concrete and the steel. The initial stage involves the chemical bonding failure until initial slippage occurs and then frictions starts to play a major role for ribbed bars. A good bonding means full transfer of tensile action to the steel (Khare). Khare showed throughout the experimental work that reduction in the compressive strength, tensile strength, the critical bonding and the maximum bonding values have resulted from an increase of pozzolanic dosage for the concrete mixes. The strain value can provide an indication of the efficiency of the overall bonding. The literature also ascertained that the compressive stresses are correlated proportionally with the shear stresses resulting from the bond test (Tavarez, Barbosa et al.,2014).

2.4 Accelerated Corrosion Testing by Impressed Current Method.

A similar testing throughout this study has been conducted to the impressed current accelerated corrosion. A known voltage is applied between the tested specimens and the cathode that are immersed in NaCl solution. In this research, the solution penetrates the specimen concrete surface and activates the NaCl solid state by dissolving it into ions. The chloride ions also penetrate the concrete pore solution to accelerate the corrosion rate. The negative terminal is connected to the electrode (cathode) and the positive terminal is connected to the steel in the beam specimen. The electrode produces cations in the NaCl solution and the electrons from the electrode creates the current which is then absorbed by the beam specimen. The electrons travel through the steel rebar in the specimen and reacts with the moisture and oxygen increasing the rate of cathodic reaction in the concrete pore solution in addition to the already produced electrons after iron dissolves in the aqueous concrete pore solution. The added electrons due to the applied current is the key to the accelerated corrosion process. Therefore, increasing the voltage by too much, will increase the cathodic reaction only keeping the anodic reaction rate constant consuming most of the water molecules. Applying a lower voltage can imitate the natural corrosion process as the water molecules are available to dissolve the iron metal in the solid state. Thus according to one research, the mass loss of steel decreased after a certain limit of applied voltage which was 4V (Shaikh & Sahare, 2016). However, the current measured increased and the time allowed for cracking decreased with increasing applied voltage (Shaikh & Sahare, 2016). Each specimen throughout this study represents the resistance where a constant voltage is applied to all the specimens by parallel connection. Resistance is an indication of the durability of the specimen which is mainly affected by permeability. The efficiency, which is the ratio of actual to the theoretical is almost constant for different variables including magnitudes of applied voltages. Thus, amount of voltage applied does not affect the accuracy of the results (Deb, 2012).

3 OBJECTIVE AND SCOPE

3.1 Objective

In this research, the main objective is to assess the impact of saline water on concrete properties and the effectiveness of different corrosion protective measures in alleviating their negative corrosive impacts from the reinforcing steel, the study also aims to investigate the cost benefits of using seawater instead of fresh water in mixing and curing of concrete.

3.2 Scope of Work

The objectives are attained through conducting experimental work on plain concrete and reinforced concrete specimen mixed and cured with seawater and conducting a feasibility study on a near coast project to evaluate the cost benefits.

This research was conducted on two categories of mixes with different water to cement (w/c) ratios, w/c=0.5 to mimic the highest bound of w/c ratios used by most projects and w/c=0.35 to have a low w/c ratio which has proven to be an effective defensive measure against chloride attack. Super plasticizer of dosage 0.75% of the cement weight was added to the low w/c mixes to increase their workability. For each w/c ratio, there were seven mixes; a fresh water mix and a seawater mix without corrosion protection measures were used as control mixes, an organic corrosion inhibitor, silica fume and epoxy steel coating were used interchangeably in 3 mixes, both silica fume and epoxy coated steel were incorporated in one mix to evaluate the effect of using more than one corrosion protective measure, and finally the latter mix was repeated using seawater from another source which have a higher salinity to generalize this study on different salinities.

4 EXPERIMENTAL PROGRAM

4.1 Material Properties

- Cement: Type I Ordinary Portland Cement.
- Fine Aggregate: Natural sand.
- Coarse Aggregate: Poorly graded crushed dolomite

- Water: Four types of water were used:
    - Fresh tape water was used for mixing and curing of the two fresh control mixes.
    - Sea water from El-Temsah Lake in El-Ismaelia governorate in Egypt was used for ten mixes. It had an average salinity of 14.19 ppt and a chloride content of 4205 mg/l
    - Seawater from the North coast in Egypt was used for two of the mixes. It had a salinity of 27.41 ppt and a chloride content of 6410 mg/l
    - Brine water that mimics the salinity of the red sea as per research was used for curing. The salinity used was 39.82 ppt with a sodium chloride content= 90% of the total dissolved solids. (Omar et al.2013 and Lenntech Water Treatment & Purification)

- Admixtures: Two admixtures were used:
    - A super plasticizer was used to increase the workability for all the low water to cement mixes and the mixes containing silica fume. The product that was used was also self-compacting.
    - Silica fume was used to decrease the permeability and the chloride ion penetration of the concrete.

- Corrosion Inhibitor: an organic corrosion inhibitor was used which forms a protective layer over the steel surface and displaces the chloride ions from the steel surface.

- Steel Coating: two layers of an epoxy one component primer that is modified with zinc was applied to steel in six mixes.

4.2 Concrete Mix Design

The mix design is shown in table 1. The cement contents were 400 kg/m^3 for normal strength concrete (w/c=0.5) and 450 kg/m^3 for high strength concrete. The coarse aggregate to fine aggregate ratio was 1.8, 15% silica fume by the weight of cement was added to 6 mixes as cement replacement, the super plasticizer was added with dosage of 0.75% by the weight of cement for all the high strength concrete mixes and with a dosage of 0.3% for the silica fume mixes in the normal strength concrete mixes

Table 1: Concrete Mixes

w/c	Water Type	Cement (kg/m^3)	Water (kg/m^3)	Coarse Aggregate (kg/m^3)	Fine Aggregate (kg/m^3)	Silica Fume (kg/m^3)	Super Plasticizer (kg/m^3)	Organic inhibitor (kg/m^3)
0.50	Fresh	400	200	1058	588	-	-	-
0.50	Ismailia	400	200	1058	588	-	-	-
0.50	Ismailia	400	200	1058	588	-	-	15
0.50	Ismailia	340	200	1058	588	60	1.2	-
0.50	Ismailia	400	200	1058	588	-	-	-
0.50	Ismailia	340	200	1058	588	60	1.2	-
0.50	North Coast	340	200	1058	588	60	1.2	-
0.35	Fresh	450	157.5	1102	612	-	3.4	-
0.35	Ismailia	450	157.5	1102	612	-	3.4	-
0.35	Ismailia	450	157.5	1102	612	-	3.4	15
0.35	Ismailia	382.5	157.5	1102	612	67.5	3.4	-
0.35	Ismailia	450	157.5	1102	612	-	3.4	-
0.35	Ismailia	382.5	157.5	1102	612	67.5	3.4	-
0.35	North Coast	382.5	157.5	1102	612	67.5	3.4	-

4.3 Tests

4.3.1 Aggregate Tests:

- Sieve analysis: this test was performed in accordance with [ASTM C136-01] to determine the gradation of the aggregates.
- Specific gravity and absorption of coarse and fine aggregates: these two tests are done in accordance with [ASTM C127-88(2001)] and [ASTM C128-01] respectively to find the specific gravity and percentage absorption of coarse and fine aggregates.

4.3.2 Fresh Concrete Tests:

Slump [ASTM C143-08], unit weight [ASTM C138], temperature and air content [ASTM C231-97] were done in accordance with ASTM standards.

4.3.3 Hardened Concrete Tests:

- Compressive strength tests: This test was done in accordance with [BS 1881]. The objective of the test was to evaluate the compressive strength of cube specimen of dimensions 15cm x 15cm x15 cm after 3 days, 7 days and 28 days. 3 cubes were tested at each testing age.
- Flexural strength of simple beam under single point loading: This test was performed in accordance with [ASTM C78]. The objective of the test is to evaluate the maximum force that a beam specimen of dimensions 15cm x 15cm x 75cm can take due to bending. The test was performed at 28 days on 2 plain concrete specimens for each mix.
- Accelerated corrosion test with impressed current method: The objective of the test is to accelerate the corrosion process in the steel from taking several years to only 2 weeks by passing an electric current through the steel in the same direction of motion of the electron forming the corrosion current. This test was conducted on two beam specimen per mix with dimensions 15 cm x 15 cm x 75 cm partially submerged in NaCl solution.
- Bonding test: This test was done in accordance with [ASTM C900-15] on cylinder specimens of 15 cm diameter and 30 cm height. A steel bar protruded from the concrete is subject to tension force and the force required to pull the steel bar from the concrete is measured to evaluate the effectiveness of the bond between the steel and the concrete.

4.4 Results and Discussion

4.4.1 Sieve Analysis

The sieve analysis showed that both the fine and coarse aggregates were poorly graded.

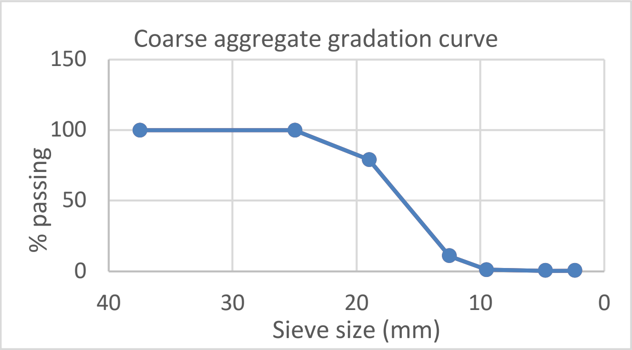

Figure 1: Coarse aggregate gradation curve

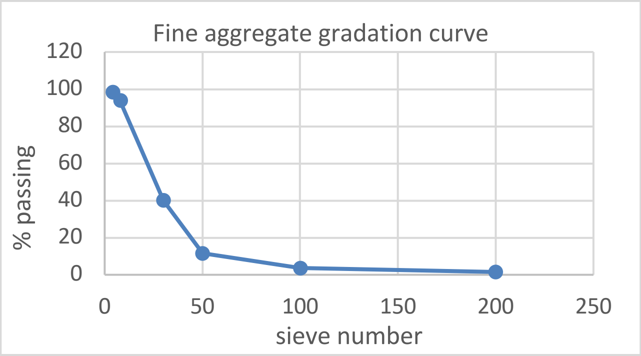

Figure 2: Fine aggregate gradation curve

4.4.2 Specific Gravity and Absorption

Table 2: Aggregate properties

	Coarse aggregates	Fine aggregates
Bulk SG	2.48	2.59
% Absorption	2.23	1.01

The specific gravity of the coarse aggregate turned out to be slightly less than the common range for dolomite of 2.55 to 2.75. The absorption of coarse aggregate is considered adequate. The specific gravity of the fine aggregate was in the common range for normal fine aggregate of 2.5 to 2.9. The absorption of fine aggregate is considered adequate as well.

4.4.3 Fresh Tests

Table 3: Fresh test results

Description	Slump	Unit Weight (kg/m^3)	Temperature (C)	Air content %
Fresh (0.5)	22.5	2,090	28.4	2%
Sea water (0.5)	18.5	2,461	23.2	1%
Organic Inhibitor (0.5)	18.5	2,361	27.1	2%
Silica (0.5)	8.5	2,146	25.3	3%
Coating (0.5)	10	2,361	26.5	1%
Silica & Coat (0.5)	4.5	2,357	23.4	3%
Higher salinity (0.5)	4	2,297	23.4	2%
Fresh (0.35)	17	2,504	26.7	1%
Sea water (0.35)	16	2,390	24	2%
Organic inhibitor (0.35)	17	2,433	25.4	2%
Silica (0.35)	10	2,347	25.7	3%
Coating (0.35)	19	2,290	25.8	3%
Silica & Coat (0.35)	1	2,076	23.1	2%
Higher salinity (0.35)	1	2,167	23.6	3%

Two batches of aggregates were used, one batch produced very workable concrete that is above the moderate limits of 5 to 10 cm except for the silica fume mixes that had moderate workability, and this is because the silica fume significantly decrease the workability of the concrete. The coating 0.5 mix also had a moderate workability. The other batch was used for the four mixes that showed relatively very low slump values and thus poor workability. The acceptable range of unit weights is between 2100 and 2400 Kg/m^3 in which five mixes did not lie. All the air content results were adequate lying between 0 and 4% and all the temperatures are adequate.

4.4.4 Compressive Strength

Using sea water increases the early strength of concrete compared to the fresh mix for normal strength concrete; however, the sea water decreases the rate of strength gain of the concrete compared to the fresh water mix and thus, at 28 days the sea water and fresh water mixes reached approximately similar results; in the literature, the fresh water topped the sea water mix by 1 to 15%. This was not the trend for high strength concrete due to errors in mixing in the fresh water mix. For normal strength concrete, the silica fume needed some time to induce strength gain which was shown at 7 days and 28 days; however, for high strength concrete, the super plasticizer along with the silica fume made the silica mix top the other mixes at all concrete ages and enabled the mix that was made by sea water to reach a compressive strength of 50 MPa. For normal strength concrete, the silica mix had the best compressive strength reaching 43.8 MPa at 28 days. Moreover, using higher salinity showed the lowest compressive strength results for both w/c atios at all ages which may suggest that the fact that sea water increases the early strength of the concrete is applicable to a certain range of salinities that needs to be further investigated. Adding the organic inhibitor did not have an effect on concrete strength. Finally, all the concrete strengths values were adequate.

Table 4: compressive strength value

Mix	3 days (MPa)	7 days (MPa)	28 days (MPa)
Fresh (0.5)	21.9	31.7	41.9
Sea water (0.5)	27.8	34.6	42.2
Organic Inhibitor (0.5)	24.2	28.9	35.5
Silica (0.5)	21.4	29.8	43.8
Higher salinity (0.5)	15.4	26.8	33.7
Fresh (0.35)	44.2	46.4	47.3
Sea water (0.35)	31.8	43.2	44.6
Organic inhibitor (0.35)	33.3	36.6	44.6
Silica (0.35)	34.7	43.6	50.2
Higher salinity (0.35)	25.0	31.1	39.0

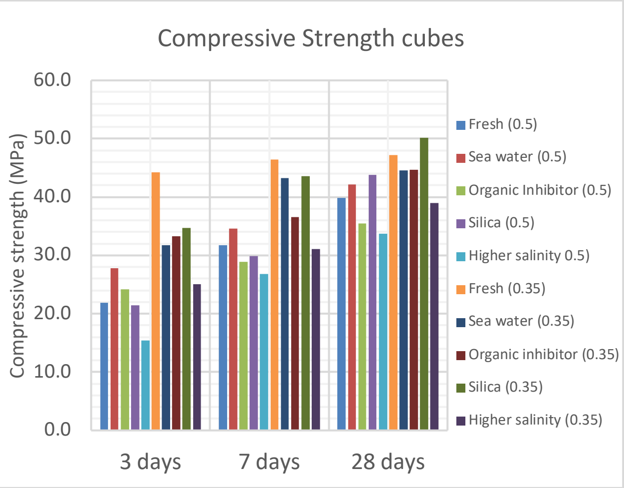

Figure 3: compressive strength results

4.4.5 Flexural Strength of Plain Concrete

All the sea water mixes yielded more flexural strength values when they were mixed and cured with sea water. This increase in the flexural strength with respect to the increase flexural strength of the fresh water mix ranges from 9% to 47%. Silica fume increase the tensile strength of the concrete; however, in a decreasing rate compared to the increase it causes to the compressive strength. Thus, the silica fumes mixes did not have a high increase in the flexural strength. The higher salinity with incorporation of silica fume mix showed relatively higher values compared to the other mixes, this might indicate that as the salinity increase, the flexural strength of the concrete increases. The organic inhibitor did not show significant effect on the flexural strength.

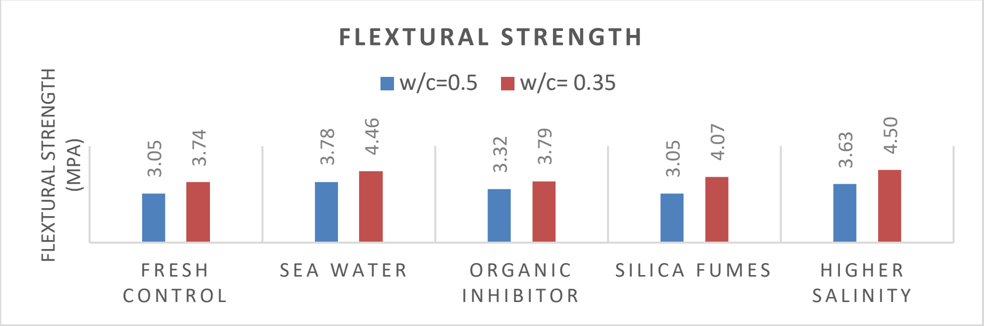

Figure 4: Plain concrete flexural strength results

4.4.6 Bonding Test

Figure 6 show the bonding test results. According to literature when the corrosion level is less than 3%, bond strength increases for the corroded bars and as the corrosion level increases beyond 3%, the bond strength increases as the corrosion increases. Leaving the sample for 28 days might have caused very slight corrosion in the steel bars which may be the reason the bond strength of the steel is the highest for the sea water mix without protective measures at the low w/c ratio. Decreasing the water to cement ratio and thus decreasing the concrete permeability and increasing the concrete strength caused the concrete to have a better bond with the steel. The inorganic inhibitor appeared to cause an increase in the bond strength between the steel and the concrete. The epoxy coating decreased the bond between the steel and the concrete; however, having a high strength concrete appears to improve the bond between the epoxy coated steel and the concrete.

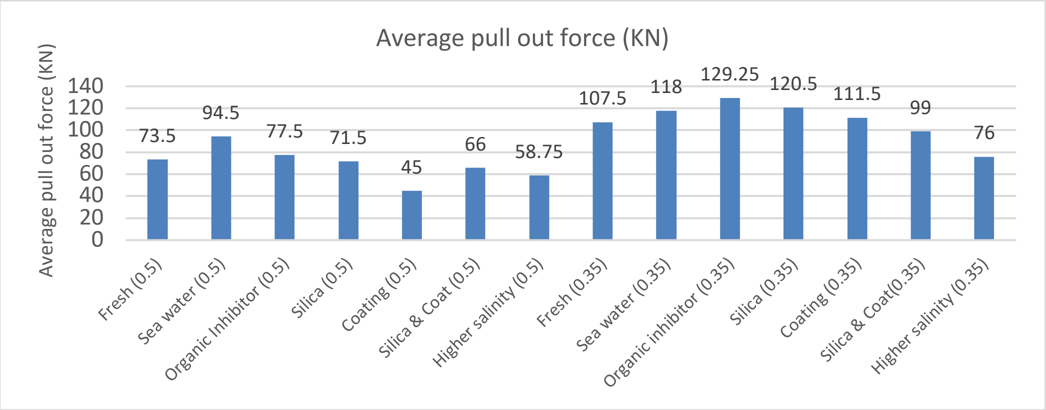

Figure 5: Bonding test results

4.4.7 Accelerated Corrosion Test

The electric currents moving through the different beams indicate different levels of electrical resistance corresponding to the different levels of protection against corrosion. The high current values indicate the low electric resistance and thus low corrosion resistance. Overall the mixtures of w/c=0.5 have less corrosion resistance than the ones that have the same protection measurements of w/c=0.35 except for the Fresh Water mix with w/c=0.35 which showed less resistance than that of w/c=0.5 Fresh Water; this may be due to problems in specimen preparation more than due to the effect of corroding chlorides. The mixtures that had epoxy coated steel bars showed higher electric resistance than those mixtures with Silica Fume and Organic inhibitor for both w/c ratios. The least electric current and thus highest corrosion resistance were in composite mixtures which shows that coating the steel with coating and incorporating silica fume can work effectively together. The beam did not fail due to time constraints in the research, however, this test gives a good indicative comparison between the different corrosion protection measures.

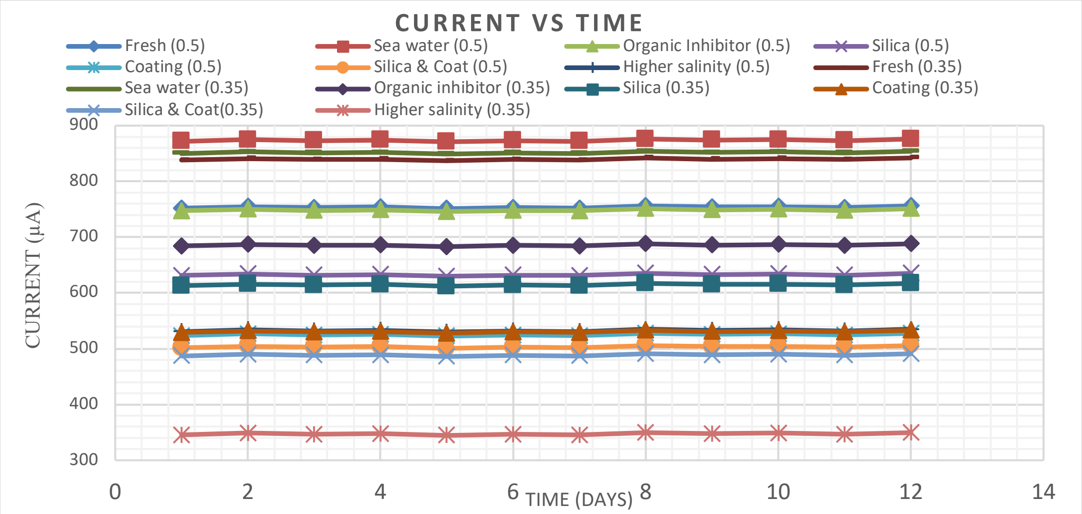

Figure 6: accelerated corrosion results

5 FEASIBILITY PRELIMINARY STUDY

For the preliminary study, a priced bill of quantities was obtained for a project in Port Said, Egypt. The quantity and the price of fresh water used in mixing was calculated. By subtracting the cost of the additional materials in each mix from the water price, we were able to observe that more than half of the mixes generated savings. Those savings are capitalized in arid countries where water is scarce or in times when using fresh water is not an option.

Table 5: Preliminary study

Mix	Material Sum (LE)	Water Price (LE)	Difference between materials and water prices (LE)
Fresh (0.5)	0	206850	206850
Sea water (0.5)	0	206850	206850
Organic Inhibitor (0.5)	37455	206850	169395
Combo 1 (0.5)	257765	206850	-50915
Silica (0.5)	257765	206850	-50915
Coating (0.5)	0	206850	206850
Fresh (0.35)	11885	206850	194965
Sea water (0.35)	11885	206850	194965
Organic inhibitor (0.35)	49339	206850	157511
Higher salinity Combo 1 (0.5)	257765	206850	-50915
Silica (0.35)	297116	206850	-90266
Coating (0.35)	11885	206850	194965
Combo 2 (0.35)	297116	206850	-90266
Higher salinity Combo 2 (0.35)	297116	206850	-90266

6 CONCLUSIONS

- Sea water concrete has the potential to replace fresh water concrete as long as protective measures are applied.
- Recent advances for protection against corrosion seem to be more effective when used in conjunction with saline water than with fresh water.
- Applying multiple protective corrosion measures to sea water concrete enhances corrosion protection more than conventional unprotected fresh water concrete.
- Incorporating silica fume reduces the air voids inside concrete which works as a mean of corrosion protection.
- Sea water increases the increase in the flexural strength of plain concrete.
- Decreasing the water to cement ratio decreases the concrete permeability which increases the resistance of concrete to corrosion
- The cost of using sea water concrete is higher than fresh water concrete due to the cost of protection materials but this gap can be closed by the cost of water desalination, environmental value of fresh water and the decrease of materials prices with higher demand.

7 RECOMMENDATIONS

- Extending the time of the accelerated corrosion test

- Using wires of same material as the steel bars or stirrups to avoid high voltage in the point of contact between different materials.
- Carrying out the bonding and flexure on samples subjected to accelerated corrosion.
- Trying a different range of salinities to investigate the applicability of the study on different salinities
- Investigating the properties of plain concrete at different salinities to know whether there is a cut off salinity after which the compressive strength of concrete do not show an increase with salinity at early ages.
- Applying high quality control measures in mixing and pouring
- If sea water is to be used in construction, it should be used first in temporary structures.

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