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Service Life of Fly Ash Concrete in Harsh Marine Climates

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***Abstract*:** *This paper used Life-365 Software to predict the service life of an offshore concrete gravity-based structure (GBS) using different dosages of fly ash. This study contained six different concrete mixtures. One of these mixtures represented the actual mixture used in Hebron project, this project was taken as a case of study that located in Newfoundland and Labrador, Canada. The other five mixtures contained different doses of fly ash, ranging from 0% to 30%. The obtained results showed that using high dosage of fly ash with concrete mixtures can decrease the chloride ion penetration and improve the service life of such structures. The results also presented the relationships between the chloride diffusion and elapsed time for each tested mixture.*

Keywords: *life-365, service life, gravity-based structure, fly ash, Hebron project.*

1. Introduction

Reinforced Concrete (RC) structures are endangered mostly in marine environments such as offshore structures. Offshore structures are exposed to harsh environmental conditions that cause durability problems and shortening in the service life of the RC structure, which lead to high maintenance and repair costs [1]. One of the most reasons that reduce the durability of offshore RC structures is the corrosion of embedded reinforcing steel [2]. The pore solution in concrete paste is alkaline which provide an oxide thin film around the steel bars to protect reinforcement from corrosion. This protection thin film dissipative when the pore solution becomes less alkaline. Alkalinity of pore solution is reduced when chloride, sulphate, or carbonate penetrate the concrete cover to reach the reinforcement. To avoid reinforcement steel bars from corrosion, concrete has to be less permeable to reduce the penetration probability of these harmful substance [3-4]. Therefore, one of the most effective techniques that use to protect concrete from corrosion and increase its service life is using low permeable concrete. Low permeable concrete can reach by increasing the fineness of cement or using supplementary cementations materials (SCMs) with high fineness such as fly ash [5-7]. Generally fly ashes have negative effect on concrete strength, especially at early ages [8]. Many researchers observed that fly ash could improve concrete strength when they are used with low water to binder (w/b) ratios [9-11], taking the advantage of using concrete admixtures to reduce the amount of water [5].

Service life in general is the period of time after installation during which all the conditions of the structure (structural part) meet or exceed the performance requirements [2]. Service life models are generally calculated by estimating two main periods [12]; initiation period and propagation period. The initiation period is the required time consumed by the chlorides to penetrate the concrete cover and accumulate at the rebar surface in sufficient amount, which breakdown its protective passive layer and initiate corrosion [13]. The propagation period starts when the chlorides are in a high concentration adjacent to the reinforcing bar. In this stage, corrosion begins and continues to increase rapidly over time.

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There are some models created to predict the service life and/or life cycles cost of concrete structures for different causes of deterioration [14]. One of these models is a computer program called Life-365 software. This software was developed for the American Concrete Institute to calculate the service life of RC structure based on Fick's law. Life-365 uses the general definition of service life of reinforced concrete as the sum of the initiation time of corrosion and the propagation time required for corroding steel to cause sufficient damage. The most important factors affecting the service life prediction in general are the quality of concrete and the environmental loads on each structure. For instance, the outside temperature, humidity, location relative to the ocean, location of the concrete element in offshore structure (submerged, tidal, or spray zone) are all affecting the service life prediction of RC structures [15].

This paper used Life-365 service life software to predict the service life for offshore concrete structures containing fly ash. The predicted service life was also compared to the service life of an existing offshore platform (Hebron offshore structure) having corrosion inhibitors to evaluate the effectiveness of using fly ash.

2. Project Overview

Hebron is a heavy oil field estimated to produce more than 700 million barrels of recoverable resources. The field was first discovered in 1980, and is located at Newfoundland and Labrador in the Jeanne d'Arc Basin 350 km southeast of St. John's, the capital of Newfoundland and Labrador, Canada. It is approximately 9 km north of the Terra Nova project, 32 km southeast of the Hibernia project, and 46 km from the White Rose project. The Hebron field will be developed using a stand-alone concrete GBS. The GBS will consist of a reinforced concrete structure designed to withstand sea ice, icebergs, and meteorological and oceanographic conditions at the offshore Hebron Project Area [16].

2.1. Typical Project Data

The service life was predicted using Life-365 Software for the base case, which represented the actual case for corrosion protection in Hebron project where corrosion inhibitors are used [16]. In addition, the service life of five mixtures containing the different dosage of FA was also calculated. To evaluate the effectiveness of used FA as SCMs and/or corrosion inhibitors compared to conventional concrete, normal concrete mixture (control mixture) with no admixtures or corrosion inhibitors was investigated.

The following inputs were considered:

i. The structure type was chosen as one dimension (1-D) type to represent the platform (slab and walls) with a total thickness of 1 m, total area of 10000 m^2, and clear concrete cover of 60 mm.
ii. The analysis period was taken as 50 years which is the expected service life of Hebron project.

2.2. Exposure and Temperature Data

Based on the project area and the software database, the monthly temperature history is forecasted, as shown in Fig. 1. The chloride exposure is defined as Marine Spray Zone because the platform height is more than (1 m) above the high-tide level but occasionally exposed to salt water spray. The surface chloride concentration (Cs) is calculated based on a build-up rate of (0.1% / year) and a maximum concentration of (1.0 % wt. conc.) (See Fig. 2)

2.3. Concrete Mixtures

Six mixtures were used for comparison between different scenarios of corrosion protection techniques. The tested mixtures are detailed as follows: a) mixture 1 was the control mixture with no FA or any SCMs and no corrosion inhibitors; b) Mixtures 2 to Mixture 5 contained different dosages of FA [15, 20, 25, 30]; c) Mixture 6 represented the actual mixture that will be used in GBS of

Hebron structure in which 25 L/m^3 Calcium Nitrite as a Corrosion Inhibitor which represent the optimum dosage of this type of corrosion inhibitor [17] (see Table 1).

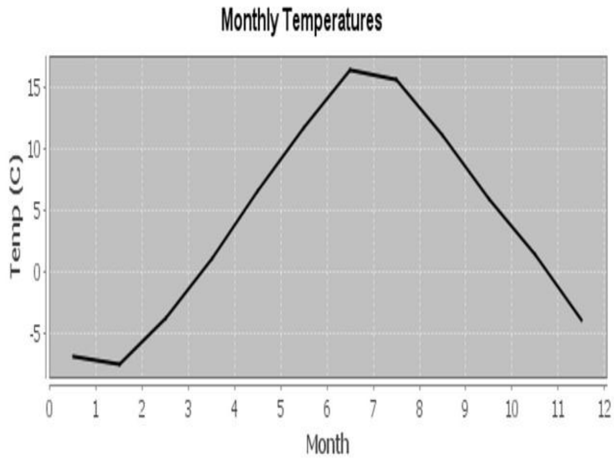

Fig. 1: Monthly temperature profile along the study period

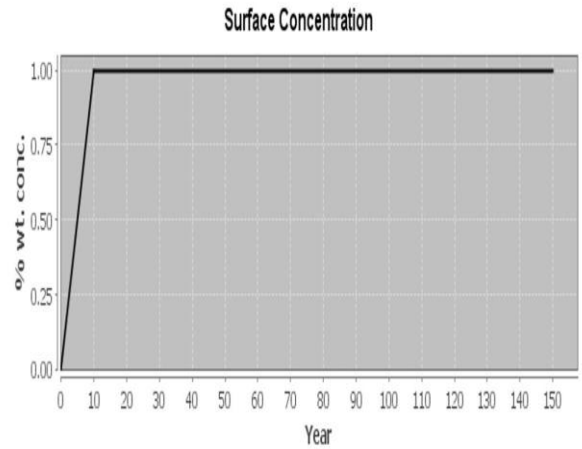

Fig. 2: Chloride surface concentration profile along the study period

TABLE I: Mixture Design

Mixture	w/b	Steel Type	SF (%)	Inhibitors (l/m^3)
1	0.25	Black Steel	-	-
2	0.25	Black Steel	15	-
3	0.25	Black Steel	20	-
4	0.25	Black Steel	25	-
5	0.25	Black Steel	30	-
6	0.4	Black Steel	-	Ca Nitrite – 25

Note: w/b. = water-to-binder; and FA = fly ash

3. Discussion of Test Results

3.1. Chloride Concentration

The above mentioned parameters were used as the inputs for analysing the service life using Life-365 software. The software uses a finite difference model to simplify the numerical solutions to Fickean diffusion of Fick's law. Six mixtures were studied to detect their effect on life service of Hebron project. Figs. 3 to 8 show the level of chloride concentration at different depths of the structural element. It can be observed that the chloride concentrations reached deeper values in the base case (Mixture 6) than the other alternative cases.

Fig. 9 shows the concentration of chlorides verses the depth of the concrete at the time of the corrosion initiation. It should be noted that the vertical dashed line in the plot represents the depth of steel reinforcement. In the Mixture 6 (base case), the chloride concentration at the depth of reinforcement reached up to of 0.37% of wt. conc., exhibiting the highest chloride threshold compared to the other investigated mixtures. As explained earlier, incorporating corrosion inhibitors tends to heighten the level of the chloride threshold, which also could contribute to increasing the lifetime before corrosion initiation. On the other hand, normal concrete mixture and mixtures with different dosages of FA showed a chloride threshold value of 0.05% of wt. conc., which represents the common values for mixtures without inhibitors. Fig. 9 shows that the mixtures from 1 to 5 had the same chloride concentration. Fig. 10 shows the concentration of chlorides at the steel reinforcement verses time. The dashed lines indicate the year of the corrosion initiation for each case. This plot shows that the base case mixture (mixture with corrosion inhibitors) reached the corrosion initiation after 28.6 years with a chloride concentration of about 0.37% which is more than the normal threshold value (0.05%). Mixture without both inhibitors and FA, showed the corrosion initiation after 16, with a chloride concentration of 0.05%, while Mixture with FA had the same chloride concentration as the normal mixture (mixture 1). The service life of mixture 5 exceeded the analysis period of the expected service life of the project because the concentration of chlorides did not reach the threshold value at end of the project life. Figure 11 shows how the concrete surface conditions change over the same period. The graph shows that all mixtures have the same surface concentrations. Figure 12 shows how the calculated concrete chloride diffusivity changes over the initiation periods. The graph indicates that Mixture with SF and mixture with MK had the same chloride diffusivity characteristics, and these oscillations are due to the effect of annual temperature variation. From the figure, it can be also observed that there is a slight difference in chloride diffusivity characteristics between mixture with SG and mixture with FA. These two graphs (Figs. 11 and 12) help with the interpretation of the performance of the concrete mixtures.

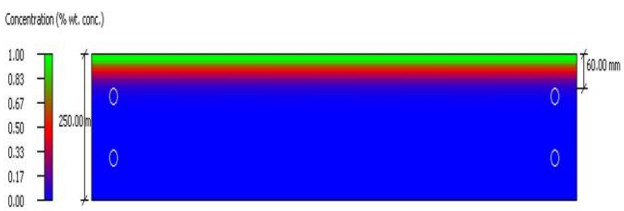

Fig. 3: Chloride Concentrations vs. Platform Depth (mixture 1 – 16 years)

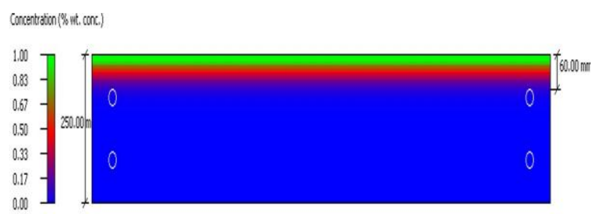

Fig. 4: Chloride Concentrations vs. Platform Depth (mixture 2 – 27.1 years)

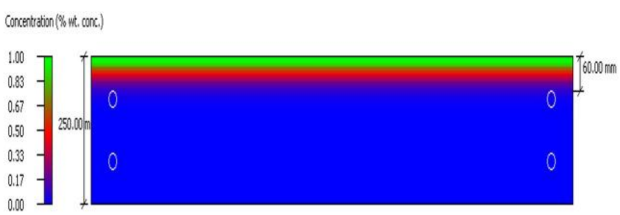

Fig. 5: Chloride Concentrations vs. Platform Depth (mixture 3 – 33.2 years)

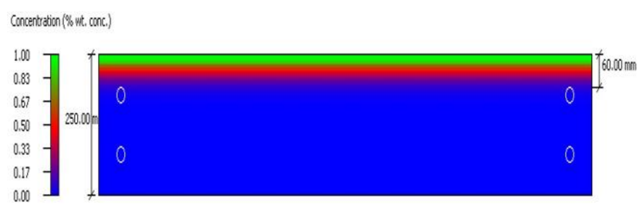

Fig. 6: Chloride Concentrations vs. Platform Depth (mixture 4 – 41.2 years)

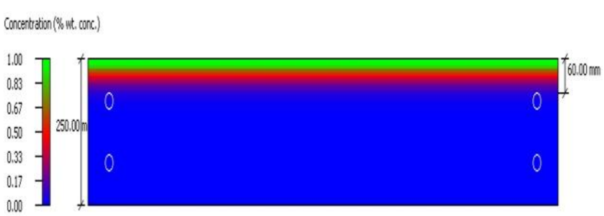

Fig. 7: Chloride Concentrations vs. Platform Depth (mixture 5 – 51.4 years)

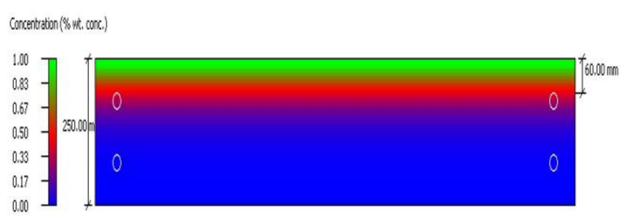

Fig. 8: Chloride Concentrations vs. Platform Depth for the Base Case (mixture 6 – 28.6 years)

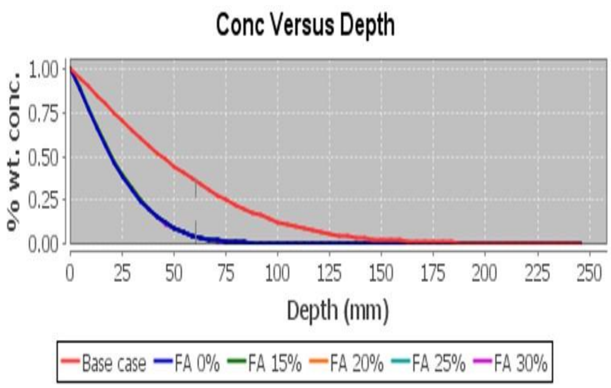

Fig. 9: Chloride Concentration vs. Depth for the all mixtures

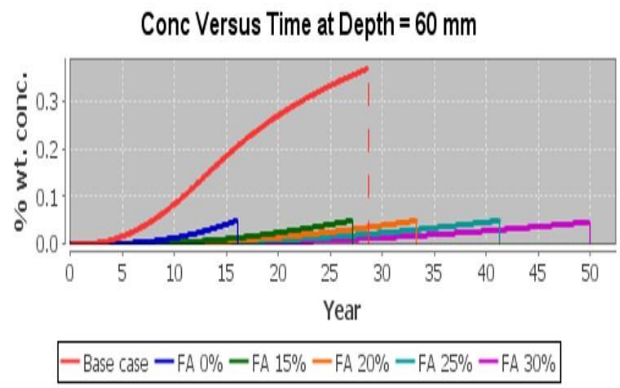

Fig. 10: Chloride Concentration vs. Time for the Six mixtures

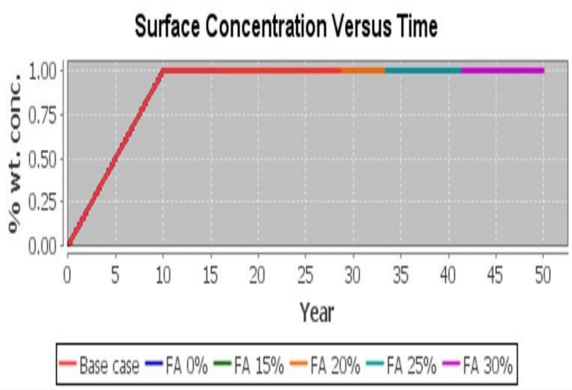

Fig. 11: Chloride Surface Concentration Profile along the Corrosion Initiation Period

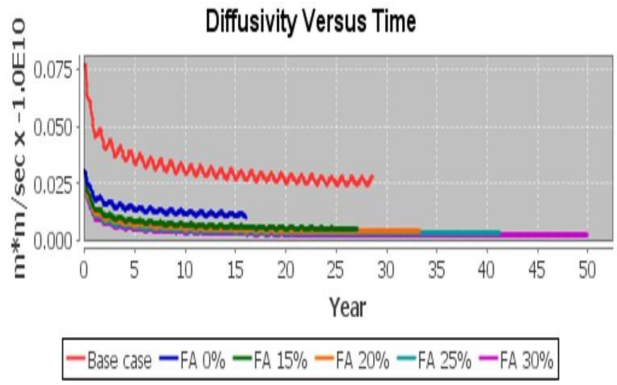

Fig. 12: Chloride Diffusivity vs. Time along the Corrosion Initiation Period

3.2. Service life

Figure 13 summarizes the total service life of the studied mixtures. It can be observed from this figure the superior effect of using FA on the service life of structures. Adding 15% FA shows a service life equivalent to the case of calcium nitrate inhibitors (25L/m^3), and both mixtures increase the durability of concrete against chloride permeability twice the normal concrete (FA=0). Using 30% FA exceeds the service life of the structure over the analysis period of the project. These results are attributed to the fact that the inclusion of FA in concrete reduces the chloride permeability. It should be noted that the propagation period was expected to be constant (6 years) for the all cases, this because the propagation period is not affected by the use of inhibitors or FA. This period is only influenced by the type of steel which was maintained constant in the analysis.

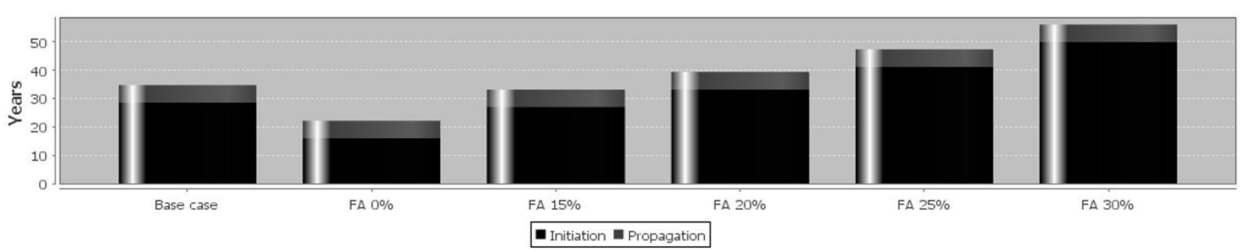

Fig. 13: Service Life Diagrams for Six Mixtures

4. Conclusions

Different corrosion protection scenarios were investigated to predict their service life. The base case, which represented the actual case of Hebron project, included Calcium Nitrite Corrosion Inhibitor (25 L/m^3), while the other five cases included different dosages of FA as partial replacements of the cement. The service life was calculated for all different cases and the following conclusions are drawn:

- The mixture that containing 30% FA exhibited the lowest chloride penetrability compared to any other mixture. The low chloride penetrability in this mixture allowed to increase the corrosion initiation times and therefore extended the service life for more than 50 years.
- The base mixture which contained Calcium Nitrite as a corrosion inhibitor showed higher service life compared to the normal concrete mixture; however, even with this relatively higher protection, the obtained service life is still lower than the expected service life of 50 years.
- The inclusion of 15% FA showed slightly lower rate of chloride diffusion, which led to slightly increase the service life of structure compared to that obtained by normal concrete mixture and showed a service life near to that obtained by using inhibitors.
- The chlorides threshold value of the corrosion initiation reached a higher level of 0.37% in the corrosion inhibitors mixture compared to all other mixtures which showed an average range of 0.05%.
- It is recommended to use FA as a partial replacement of the cement rather than using corrosion inhibitors in order to obtain lower chloride penetrability and minimum probability of reinforcement corrosion.

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