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A Comparative Study on Service Life Prediction of Hebron Gravity-Based Structures

Mohamed K. Ismail[1], Assem A. A. Hassan[1] and Mahmoud E. Said[1]
[1] Faculty of Engineering and Applied Science, Memorial University of Newfoundland, St. John's, Newfoundland, Canada.

Abstract: *This study investigates the effect of using different supplementary cementing materials (SCMs) (fly ash, slag, silica fume, and metakaolin) on the service life of Hebron gravity-based structure (GBS) located in Newfoundland, Canada. Life-365 Software was used to predict the service life of the investigated concrete mixtures. In total six mixtures were developed, one of these mixtures represented the actual mixture used in Hebron project (where corrosion inhibitors are used) while other four mixtures were developed containing the optimal dosage of the investigated SCMs. Also, a normal concrete mixture without any admixtures was developed for comparison. The results showed that using metakaolin or silica fume can greatly contribute to decreasing the chloride ion penetration and improving the service life of GBS. The results also presented the relationships between the chloride diffusion and elapsed time for each tested mixture.*

Keywords: *service life prediction, gravity-based structure, supplementary cementing materials, life-365, Hebron project*

1. Introduction

Reinforced concrete in severe environments, for example that used in offshore structures, is deteriorating at a dangerous rate due to concrete durability problems. For this reason, such structures should be given a special design consideration to extend its service life. Moreover, periodical monitoring during the structure service time is urgently needed to detect any deterioration. The most critical factor for this deterioration is the corrosion of embedded reinforcing steel. Concrete is naturally alkaline; this alkalinity is important in providing protection against corrosion of the reinforcing steel [1]. However, chlorides from deicing salts, groundwater, or seawater could penetrate the concrete cover and reach the reinforcing steel causing a reduction of the concrete alkalinity [2]. Once the percentage of the chloride around the steel bar exceeds the threshold needed for corrosion initiation, the corrosion starts and followed by propagation through steel bars, which eventually leads to concrete cover cracking, mass loss in the reinforcing bars, and ultimately delimitation of the concrete cover, which typically lead to significant deterioration and shorting in service life [3].

Different techniques have already been applied to protect reinforcing bars from corrosion or to minimize its effect. Typically most of these techniques are based on adding corrosion inhibitors additives to concrete mixture and/or coating the reinforcing bars by an insulating coating material. In addition, some researchers have proposed other ways to prevent corrosion, for example, using stainless steel instead of ordinary bars [4]. Alternatively, sealing the concrete surface to prevent chloride diffusion through the concrete cover is used in a number of structures. Finally, high performance concrete (HPC), that exhibits very low permeability, has been successfully employed to extent the time to corrosion initiation. Supplementary cementing materials (SCMs) such as fly ash (FA), slag (SG), silica fume (SF), and metakaolin (MK) can be used to obtain HPC to improve the long term durability and strength properties of the concrete [5-6].

Significant research has been conducted to study the influence of mixtures containing different SCMs on both normal and high performance concrete. The literature showed that SF and/or MK are the most effective

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SCMs could enhance the durability of concrete [7], decreasing chloride penetration [8]. MK also reduces the risk of alkali–silica reaction [9] and increases the resistance of concrete to sulfate attack [10]. Using SF or MK has a direct impact on enhancing the mechanical properties of concrete mixture [11-12], high chemical resistance, and long service life.

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 [1]. Service life models are generally calculated by estimating two main periods [15]; 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 [16]. 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. There are some models created to predict the service life and/or life cycles cost of concrete structures for different causes of deterioration [17]. 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 [18].

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

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 offshore Newfoundland and Labrador in the Jeanne d'Arc Basin 350 km southeast of St. John's, the capital of Newfoundland and Labrador. 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 water depth at Hebron is approximately 92 m. 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 [19].

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 [19]. In addition, the service life of four mixtures containing the optimal dosage of SF, FA, SG, and MK was also calculated. To evaluate the effectiveness of used different 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:

- 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.
- 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)

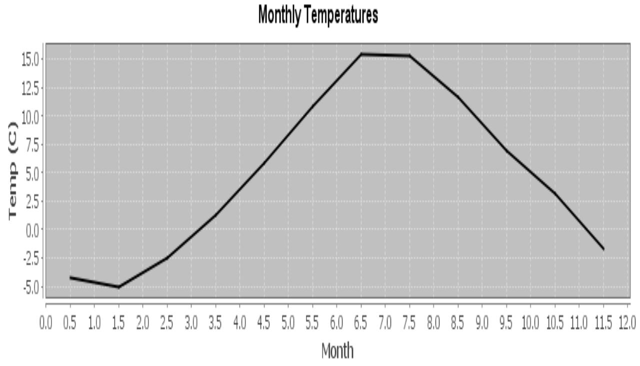


Fig. 1: Monthly temperature profile along the study period

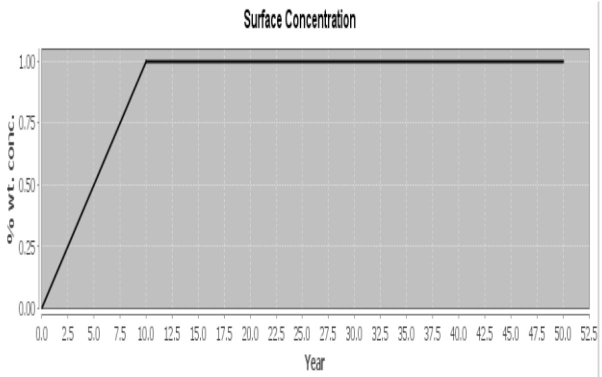


Fig. 2: Chloride surface concentration profile along the study period

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 SCMs and no corrosion inhibitors; b) Mixtures 2-5 contained different SCMs (FA, SG, SF, and MK) with their optimal dosage [6, 10-13].; 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 [20] (see Table 1).

TABLE 1: Mixture Design

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

Note: w/b. = water-to-binder; and SCM = supplementary cementing materials

3. Discussion of Test Results

3.1. Chloride Concentration

The above-mentioned parameters are used as the inputs for analyzing 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 are 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.

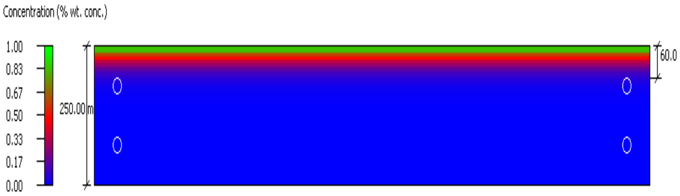


Fig. 3: Chloride concentrations vs. platform depth for the normal concrete (9 years)

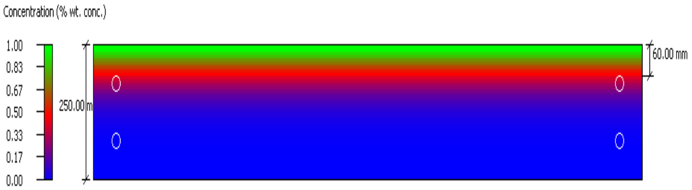
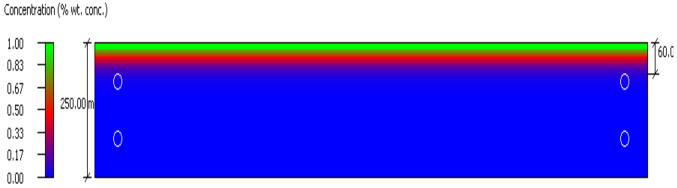


Fig. 4: Chloride concentrations vs. platform depth for the FA (15 years)



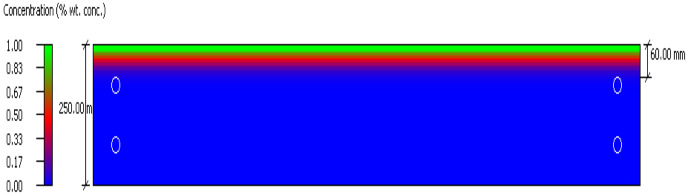


Fig. 5: Chloride concentrations vs. platform depth for the SG (12 years)

Fig. 6: Chloride concentrations vs. platform depth for the SF (50 years)

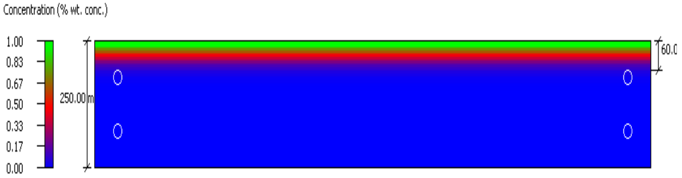


Fig. 7: Chloride concentrations vs. platform depth for the MK (50 years)

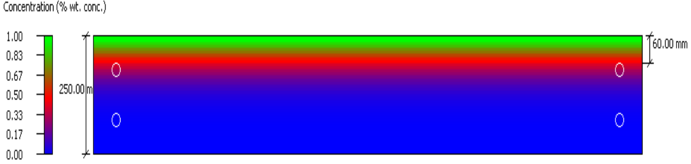
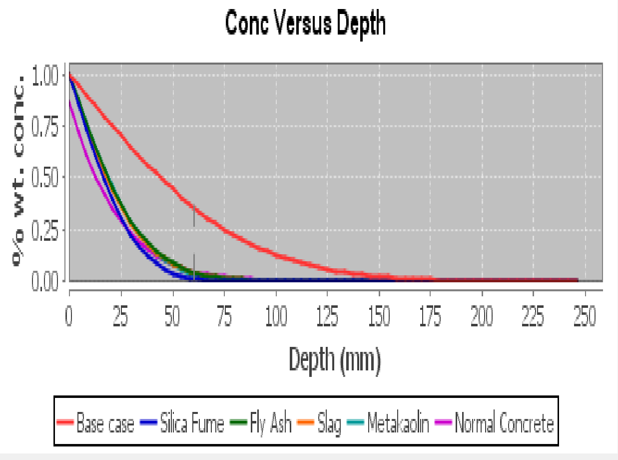


Fig. 8: Chloride concentrations vs. platform depth for the base case (32 years)

Figure 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 mixture with inhibitors (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 SCMs showed a chloride threshold value of 0.05% of wt. conc., which represents the common values for mixtures without inhibitors. 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 32 years with a chloride concentration of about 0.37% which is more than the normal threshold value (0.05%). Mixture with FA or SG, showed the corrosion initiation after 15 and 12 years, respectively, with a chloride concentration of 0.05%, while Mixture with SF or MK had the same chloride concentration as the mixtures without inhibitors but after 50 years. The service life of mixtures 4 and 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.



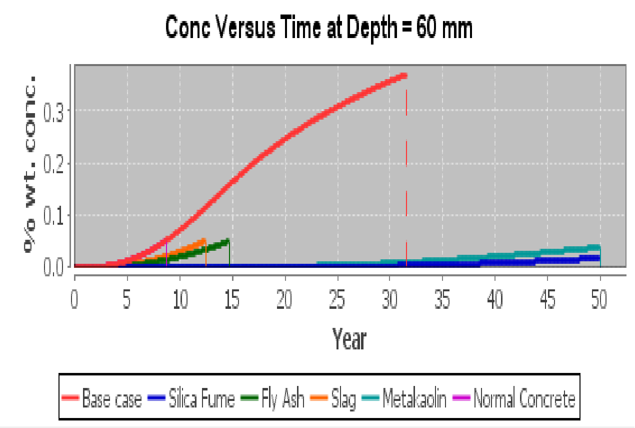


Fig. 9: Chloride concentration vs. depth for the six cases

Fig. 10: Chloride concentration vs. time for the six cases

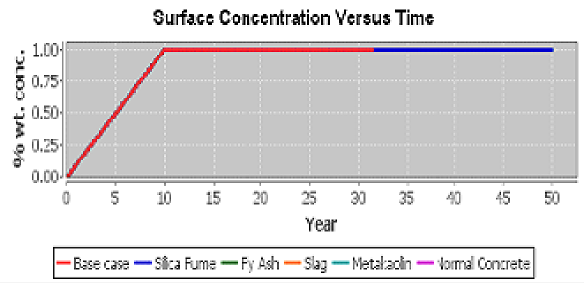


Fig. 11: Chloride surface concentration profile along the corrosion initiation period

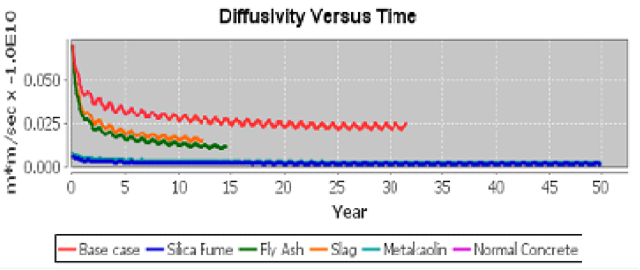


Fig. 12: Chloride diffusivity vs. time along the corrosion initiation period

3.2. Service Life

Fig. 13 summarizes the total service life of studied mixtures. It can be observed from this figure the superior effect of using MK and SF on the service life of structures in which these percentages contributed to increasing the lifetime of structures 3.7 times higher than that obtained by normal concrete mixture. These results could prove the superior effect of using MK and SF concrete on reducing the concrete permeability and chloride penetrability. Meanwhile, adding 20% FA or 20% SG had a slight enhancement on the service life of structure compared to normal concrete mixture. This could be attributed to their limited ability to reduce the chloride penetrability compared to MK and SF. Using corrosion inhibitors (25 L/m^3 calcium nitrite) showed also an improvement reached up to about 2.5 times higher than normal concrete mixture. Moreover, this property (chloride permeability) is believed to enhance along the age of the concrete because of the continuing hydration of it. The propagation period was expected to be constant (6 years) for all cases, this was because the propagation period is not affected by the use of inhibitors or SCMs. This period is only influenced by the type of steel which was maintained constant in the analysis.

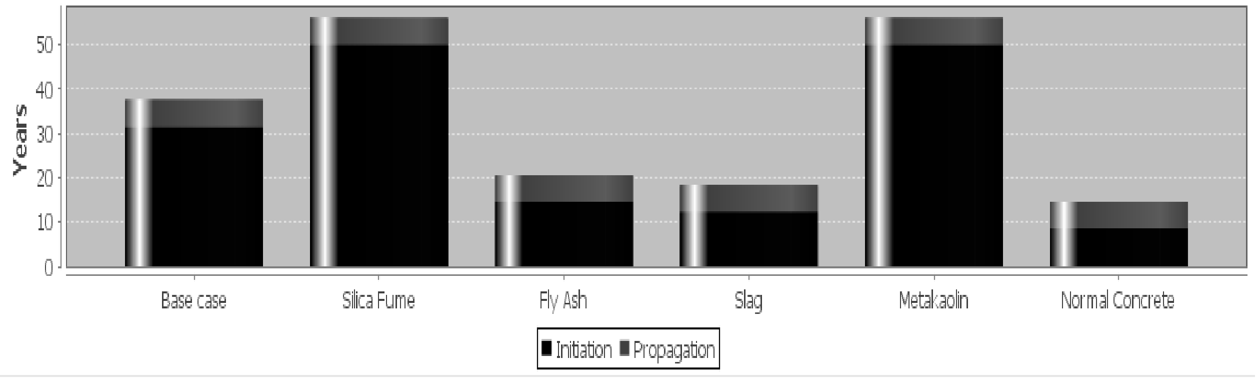


Fig. 13: Service life diagrams for six mixtures

4. Conclusions

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

- Mixtures containing 20% MK or 15% SF exhibited the lowest chloride penetrability compared to any other mixture. The low chloride penetrability in these mixtures allowed to increase their corrosion initiation times and therefore extended their service life of 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 life service is still lower than the expected life service of 50 years.

The inclusion of 20% FA or 20% SG 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.

- 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 of MK or SF as partial replacements 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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