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Economic Service Life of RC Structure Based on Corrosion Initiation Time

Md. Shafiqul ISLAM[*,1]

*1 *Assistant Professor, Department of Civil Engineering, Rajshahi University of Engineering & Technology, Bangladesh,*

Abstract

Target service life of the structure specified by the codes and standards for RC infrastructures has failed to achieve due to uncertainties at the time of construction of structure and at exposure to real environment. Moreover, the more resistivity of the cover concrete, the larger is the service life and thus higher is the cost incurred by the owner. Therefore, economic service life (ESL) has more value than considering engineering service life, where both the failure and the cost consider parallel in the prediction of service life. A statistical model to determine the time to initiate corrosion due to chloride attack to the RC member and subsequent repair considering all costs incorporated is taken into account in this research. Cost minimization model is used to calculate economic service life where initial cost, repair cost and gain from revenue for the structure are paid attention. Further, a correlation between corrosion initiation time (CIT) and economic service life (ESL) is proposed.

Keywords: corrosion initiation time, economic service life, random sampling

1. Introduction

Serviceability limit state design specification includes many criterions to fix the required durability of reinforced concrete structure. But still it is very difficult to control the performance of real structure in severe aggressive environmental attack. Chloride induced steel corrosion is one of the major deterioration problem for steel reinforced concrete caused by salty environment.

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[*] Corresponding author: Email: islam94001@*yahoo*.com

Since 1960’s chloride de-icing salts used on roadways in United States have been increased greatly; about 10 million tons of salts are used annually [1]. Thus the cost of highway bridge repair in US is increasing greatly. The Ministry of Land, Infrastructure, and Transport forecast that in 2025 annual maintenance cost in Japan will reach approximately 9 trillion yen, which will represent approximately 70 to 80% of total annual construction investment forecast for that year [2]. However cost effective maintenance plan and proper decision making can efficiently reduce the life cycle cost of infrastructure like bridges. To assist the decision makers for initiating better maintenance strategy, it is necessary to predict service life correctly. A better service life model would assists planners to estimate the time to first repair and subsequent rehabilitation with greater accuracy.

A statistical based model which accounts for the variability of input variables would more accurately predict the time to first repair and subsequent rate of deterioration. A model using statistical distributions has been developed for marine bridge substructures [3]. Statistical distributions are used for the surface chloride ion concentration, clear concrete cover depth and chloride ion coefficient. A discrete value is used for the chloride corrosion threshold concentration. Uncertainty of the influence of the chloride corrosion initiation concentration is addressed by solving the model using a number of discrete initiation values. The cover depth, surface chloride content and chloride diffusion coefficient are considered to be normally distributed.

One common modern statistical technique is called Monte Carlo simulation. Monte Carlo is a general class of repeated sampling methods where a desired response is determined by repeatedly solving a mathematical model using values randomly sampled from probability distributions (often assumed) of the input variables [4]. Within the category of Monte Carlo methods, a resampling method called bootstrapping uses the same repetitive sampling procedure but uses data to define the parameters for the distributions or samples directly from the existing data [5]. Parametric bootstrapping was used in this research.

Once the time to initiate corrosion is known from service life model, repairing is done to improve the health condition of the structure deteriorated and thus a matter of costing comes forward to the owner. The owner shall recognize that all structures - regardless of building material - will age and deteriorate with time. Hence, he must clarify his needs up front regarding design service life. When doing so, his decision has not only impacts on the short term cost of creating the structure but just as much on the long term costs for maintaining and repairing the structure to comply with his long term performance requirements.

The requirement for a specific service life performance of a structure is closely associated with the short and long-term costs of this requirement. The owner must therefore acknowledge that he has to take decisions on both the service life and on the associated performance requirements, and he must accept both the short and the long-term costs – and savings - associated with his decisions.

A different way of looking at the economic replacement decision was presented in Drinkwater and Hastings' repair limit theory [6]. Repair limit theory is not applied until an object has broken. The concept behind repair limit theory is that there exists some amount below which it is economically sound to repair the object. If the estimated cost of the repair is greater than that limit, the repair should not be undertaken and the object should be discarded or replaced.

However, the study will assists the owner to continue the subsequent repairing until economic service life (ESL) reaches for the structure deteriorated by chloride attack. The repairing for such deteriorated structure should not be undertaken beyond the limit of economic service life (ESL).

2. Methodology

Since most observations indicate that the transportation of chlorides in concrete is diffusion controlled [7], an apparent diffusion process, based on Fick's second law, can be used to model the time for chloride to reach and initiate corrosion at first repair and rehabilitation reinforcing steel depths. When solved for the condition of constant surface chloride and a one-dimensional infinite depth, Fick's second law takes the following form [8].

$$C_{(x,t)} = C_o\left(1 - erf\,\frac{x}{2\sqrt{Dt}}\right) \qquad (1)$$

Where $C_{(x,t)}$ is chloride concentration at depth and time, C_o is surface chloride concentration, D is apparent diffusion coefficient, t is time for diffusion, x is concrete cover depth and erf is statistical error function. When $C_{(x,t)}$ is set equal to the chloride corrosion initiation concentration and Eq. 1 is solved for t, the time for the diffusing chloride ions to initiate corrosion is achieved.

$$t = \frac{\left(\frac{x}{2y}\right)^2}{D} \qquad (2)$$

$$y = erf^{-1}\left(1 - \frac{C_{(x,t)}}{C_o}\right) \qquad (3)$$

However, for a given concrete structure, the values of $C_{(x,t)}$, C_o, D and x are random variables. A solution to Eq. 2 will result distribution of corrosion initiation time (CIT) from which the mean value is considered as the time for first repairing. It is essential to conduct repairing after the structure goes beyond the safety limit. Repairing improves performance of the structure to its initial condition. But, again it deteriorates with age and requires repairing. The length of service that the structure needs repairing is regarded as economic service life (ESL) in this research.

After this time has expired, there is at least one other alternative (replace, rebuild, etc.) which is more economical than keeping the structure in its present state. The models attempt to find the optimum length of service by using a variety of techniques based on the science of economics.

There are three basic theories in the field of economics to understanding the repair limit. They are: *the cost minimization model, the profit maximization model, and the repair limit model*. Cost minimization and profit maximization theories developed on parallel paths beginning in the 1920's. Repair limit theory is relatively new—it was first published in the 1960's.

Most costs associated with a structure can be placed in one of two categories: ownership costs and operating costs. The average cost of ownership for a given structure should decrease the longer it is kept. This is because most of the capital costs involved with owning a structure is incurred as soon as it is constructed. As time goes on, the initial construction cost is spread over a longer time span and thus the average cost decreases. The average cost of operating for a given structure should increase the longer it is kept. For example, when the structure is new, repair costs should be relatively small and infrequent while the structure is in service, repairs become more frequent, and sometimes more costly. Cost minimization strives to find a balance point between decreasing ownership costs and increasing operating costs. There are three types of costs: average ownership cost, average operating cost, and average total cost as listed in the following [9]:

$$AverageOwnershipCost = \frac{P_0 - S_t}{L_t} \qquad (4)$$

$$AverageOperatingCost = \frac{\sum_0^t E_P}{L_t} \qquad (5)$$

$$AverageCost\ per\ period\, at\ age\, L_t = \frac{P_0 + \sum_0^t E_P - S_t}{L_t} \qquad (6)$$

Where P_0 is initial construction cost, E_p is the repair cost for the period, S_t is revenue earn, L_t is structure age at time t.

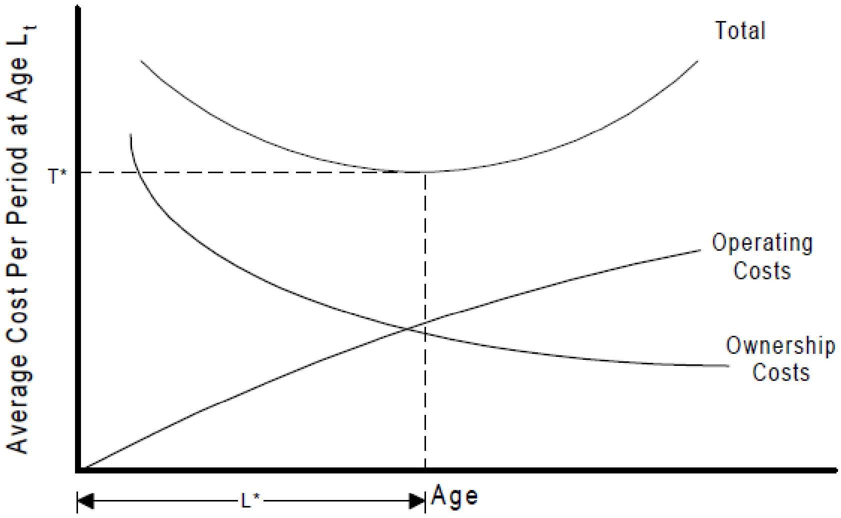

Fig. 1 Cost minimization model.

Average costs are calculated by taking the cumulative costs incurred up to a given point in time and dividing these costs by structure age. Average cost curves are developed for ownership costs and for operating costs. The sum of these two curves, the *average total cost* curve, slopes downward initially when operating costs are low and the average cost of capital is decreasing. The minimum value of average total cost is T*, the point where the slope of the curve is zero. The optimum economic life, L*, is that period which ends when the sum of owning and operating costs reaches a minimum.

3. Results and discussions

3.1 Effect of design parameters on corrosion initiation time

To predict corrosion initiation time Eq. 2 was modelled in Microsoft excel generating random numbers of the input variables. Diffusion coefficient for ordinary Portland cement was calculated based on w/c ratio using the following equation [10].

$$\log_{10} D = 3.9(w/c)^2 + 7.2(w/c) - 2.5 \qquad (7)$$

Where D is diffusion coefficient in cm^2/yr., w/c is water to cement ratio. Threshold chloride content, surface chloride, cover depth, and diffusion coefficient were modelled in the nature of normal distribution with coefficient of variation (COV) as 0.1 in Excel using the function *norminv(rand(),mean,sd)*. The mean value of cover depth was considered as 4, 5, 6, and 7 cm and w/c ratio was taken as 0.3, 0.4, 0.5, and 0.6 in the simulation. The mean values for surface and threshold chloride were used 4 kg/m^3, and 1.8 kg/m^3 as reported in the reference [11] for the structure situated in atmospheric zone. Sampling was done for 5000 times and corrosion initiation time (CIT) was calculated for each of the cases. **Fig.** 2 is the distribution of corrosion initiation time (CIT) for concrete having w/c ratio and cover depth as 0.3, and 5 cm, respectively whereas; **Fig.** 3 is the distribution of corrosion initiation time (CIT) for concrete having w/c ratio and cover depth as 0.6, and 5 cm, respectively.

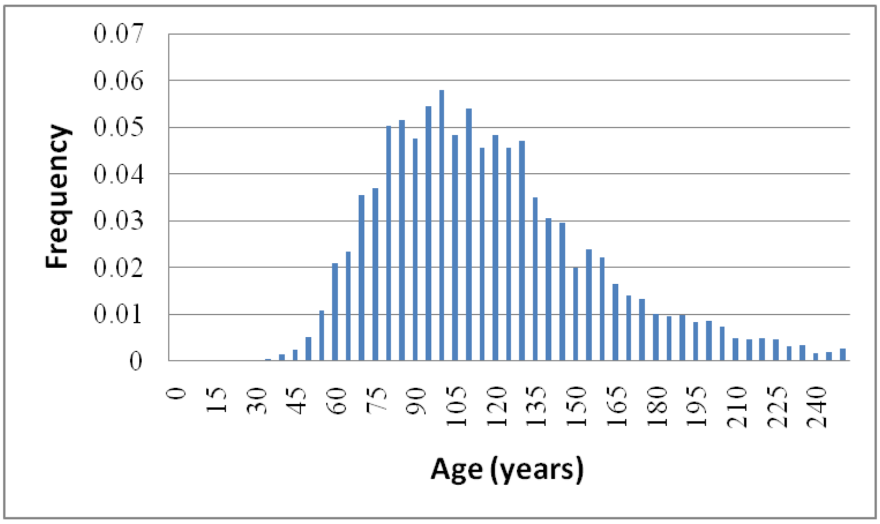

Fig. 2 Distribution of corrosion initiation time (w/c ratio = 0.3 & cover depth = 5 cm).

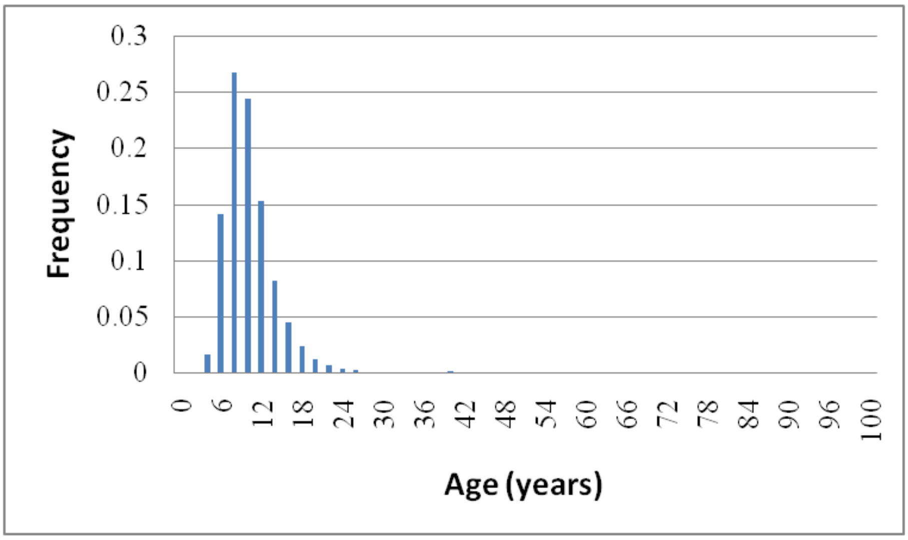

Fig. 3 Distribution of corrosion initiation time (w/c ratio = 0.6 & cover depth = 5 cm).

To interpret the results of simulation, it is important to understand the sensitivity of the various input values on predicted CIT. **Fig. 4** presents the relationship between CIT and w/c ratio. Separate curves are plotted for values of cover depth equal to 4, 5, 6, and 7 cm. similarly **Fig. 5** presents the relationship between CIT and cover depth. Separate curves are plotted for values of w/c ratio equal to 0.3, 0.4, 0.5, and 0.6.

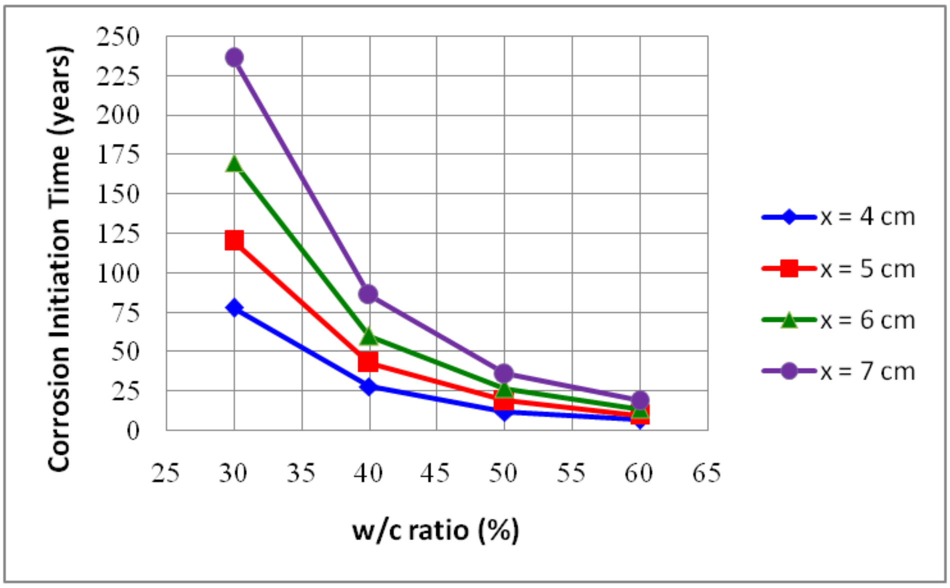

Fig. 4 Effect of w/c ratio on corrosion initiation time for different cover depths.

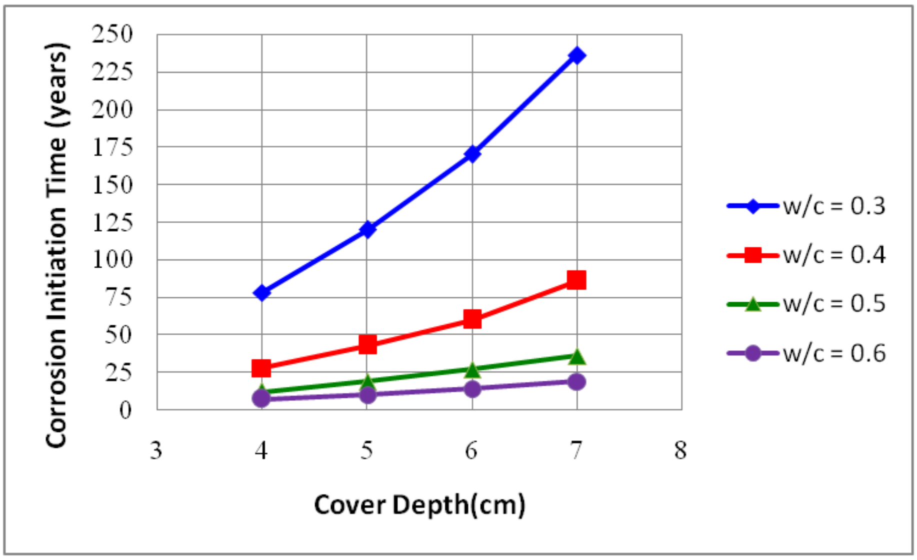

Fig. 5 Effect of cover depth on corrosion initiation time for w/c ratio.

In **Fig. 4**, CIT decreases rapidly with non-linearity whereas, in **Fig. 5** CIT increases almost linearly which supports the proposition that corrosion initiation time (CIT) is much more sensitive to w/c ratio than that of cover depth.

3.2 Calculation of ESL from CIT

It is very important for both the owner and engineer to understand the effect of design parameter on the prediction of corrosion initiation time (CIT) and thus the effect of corrosion initiation time (CIT) on required total cost of the structure throughout its lifetime as the repairing cost depends on the initiation of corrosion. The lifecycle cost of the structure was calculated under the following conditions:

- Repair interval: subsequent repairing will take place same as corrosion initiation time (CIT)
- Initial cost: same as corrosion initiation time (CIT), the more is the resistivity of the concrete, longer is the CIT, and higher is the initial cost
- Repair cost: 10% of the initial cost

In this research, repair work is to be repeated at interval same as CIT after the first repair work. Strictly speaking, the validity term of repair should change depending on the environmental conditions. However, repair design, for example, selection of appropriate method corresponding to environmental conditions, improvement done by specific repair method, prediction of deteriorated repaired concrete, has not been established at this moment. It is therefore difficult to consider the effect of various aspects of repairing in the proposed calculation at this moment.

Example calculations of average costs for two different cases are shown in **Fig. 6** and **Fig. 7**. **Fig. 6** corresponds to the concrete having w/c ratio 0.3 and cover depth 4 cm and **Fig. 7** corresponds to the concrete having w/c ratio 0.6 and cover depth 4 cm, respectively.

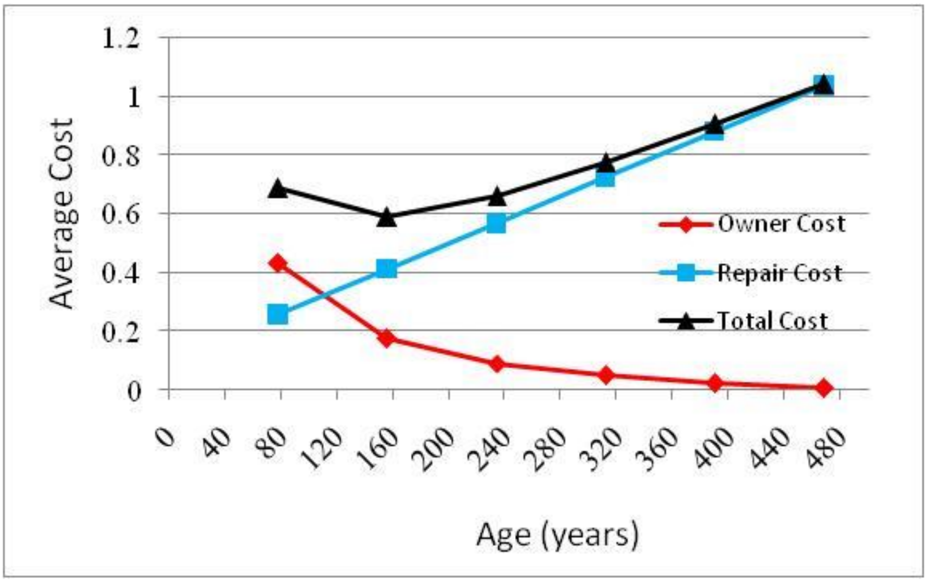

Fig. 6 Average cost curves (w/c ratio = 0.3 & cover depth = 4 cm).

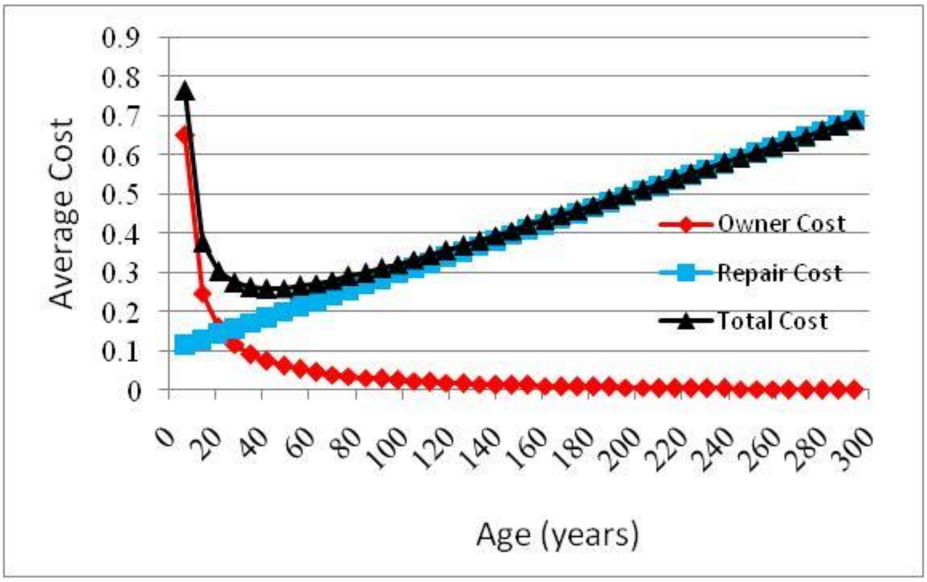

Fig. 7 Average cost curves (w/c ratio = 0.6 & cover depth = 4 cm).

In both cases repair is increasing and owning cost is decreasing. Thus, we have a minimum of total cost on the scale of service life. The owner will face monetary loss if operation of the structure continues after this point of time on service life scale.

Table 1- Simulation variables

	Mean Value of the parameters			
	Threshold Chloride (kg/m^3)	Surface Chloride (kg/m^3)	w/c Ratio	Cover depth (cm)
Case 1	1.8	4	0.3	4
Case 2	1.8	4	0.4	4
Case 3	1.8	4	0.5	4
Case 4	1.8	4	0.6	4
Case 5	1.8	4	0.3	5
Case 6	1.8	4	0.4	5
Case 7	1.8	4	0.5	5
Case 8	1.8	4	0.6	5
Case 9	1.8	4	0.3	6
Case 10	1.8	4	0.4	6
Case 11	1.8	4	0.5	6
Case 12	1.8	4	0.6	6
Case 13	1.8	4	0.3	7
Case 14	1.8	4	0.4	7
Case 15	1.8	4	0.5	7
Case 16	1.8	4	0.6	7

In all cases coefficient of variation (COV) is fixed to 0.1

A total number of 16 cases, as listed in **Table 1**, were analysed with w/c ratio varied from 0.3 to 0.6 and cover depth from 4 to 7 cm and corrosion initiation time (CIT) were calculated for each case in the nature of distribution. All the values in the table represent the mean having constant COV as 0.1. Corrosion initiation times (CIT) were put in the cost minimization model and economic service life (ESL) were calculated.

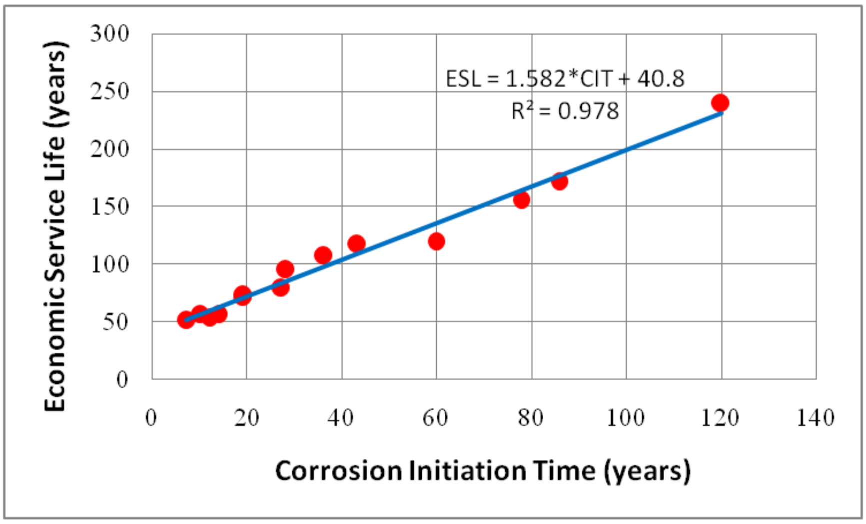

Fig. 8 Correlation between corrosion initiation time and economic service life.

Fig. 8 shows the relationship between corrosion initiation time (CIT) and economic service life (ESL) and a linear dependency is found.

4. Conclusions

The following conclusions can be drawn from the analysis of concrete structure subjected to reinforcement corrosion caused by chloride damage.

(1) The time to corrosion initiation is not highly sensitive to cover depth as it is to the diffusion coefficient.

(2) Cost minimization model helps the owner to understand the concept of economic service life (ESL) beyond which the structure should not be operated.

(3) Economic service life increases with the increase of corrosion initiation time and the trend is linear.

(4) A small improvement by repair can raise the structural health condition to its initial level if the cover resistant of the structure was initially poor while it was constructed. Small improvement by repair costs less and thus a number of times repairing may be conducted. Therefore, economic service life (ESL) is 3 to 5 times the corrosion initiation time (CIT) for the structure having poor cover resistant. But, for the structure having good cover resistant to corrosion, it requires large improvement at the time of first repair to reach to its initial level of health condition and thus huge repair cost is necessary. Therefore, economic service life (ESL) is found by cost minimization as twice the corrosion initiation time (CIT).

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