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# Life Cycle Cost Optimization for the Design of Reinforced Concrete Structures

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**Abstract:** ***Concrete is widely used as a traditional material. As the designing aspects of the concrete structures are concerned, the initial costs are considered. On the basis of the past experience, it was found that with the passage of time, degradation in the concrete structures occurs and it affects the properties of concrete, due to which the concrete structures become unable to maintain its durability. So there is high need to maintain the concrete structures time to time to give its performance well and during maintenance there must be proper use of limited resources. To overcome the problems of detoriation of concrete structures and new structures, some methodologies are developed which define the number of maintenance required. In the present research work, a procedure which is based on a life cycle cost is developed. Structural durability and cost optimization are united. The principle in design is increasing defined limit state on which service life is based.***

**Keywords:** Concrete Structures, dedgradation, durability, maintenance, life cycle, Cost

## 1. Introduction

### 1.1 Background

Structural design of concrete structures traditionally considered compressive strength and highlights on construction and design. The reliability of a structure reduces when the material degrades. Therefore, time to time maintenance of deteriorating structures is required for the reliability and structural performance of concrete structures. During inspection and maintenance, there must be proper use of limited resources. The present work proposed methodologies to determine the expected life, required maintenance and methods for calculating life-cycle cost of structures. Apart the construction cost, life cycle cost includes the cost of repair and maintenance. Generally, the design of concrete structures based on durability is dependent on certain rules for satisfying basic requirement of materials, material components and structural dimensions. Examples of such rules are the need for at-least concrete cover, maximum water/cement ratio and minimum cement content. With such system, it is not possible to develop a relationship between condition and structural life. Therefore, it is needed to develop and implement a proper design methodology to provide a proper base so that in its service life, the concrete structures could perform well.

### 1.2 Life Cycle Cost

Life cycle cost (LCC) is the total cost for a customer of a machine or apparatus, including procuring costs and operating costs (which include preservation, repair, and energy costs). Future operating costs are discounted to the time of purchase, and summed over the lifetime of the appliance or equipment.

The life-cycle cost of a structure includes the sum of the present value of all expected costs concerning the construction plus all the expenses related to maintenance and management of the structure during its life. Life-cycle cost usually refers to the deterioration due to mechanisms such as corrosion and risk related to natural hazards, such as wind or earthquake.

Total life cycle cost can be estimated by considering construction cost (Pc), inspection cost (Pi), maintenance cost (Pm), and renewing/ replacing cost (Pr), so the formula is

$$\text{Total cost} = Pc + Pi + Pm + Pr + \text{miscellaneous costs}$$

### 1.3 Motivation for Life Cost Analysis

During design of concrete structures, it is common to adopt more than 50 years design life. However, analyses of a number of case studies worldwide have indicated that the actual design life can be significantly reduced due to premature deterioration resulting from exposure to destructive surrounding environments. A closer analysis of the cost of rehabilitation of these structures has raised some interesting questions.

## 2. Literature Review

From the starting of the construction up to the end of life of structure, life cycle cost is determined by the sum of its starting up to end. Many researchers worked on it. Narassimha (2006) gave idea that durability is dependent on maximum water cement ratio, minimum cover of concrete and minimum content of cement. But the idea was not so good. So there is a need to make a suitable design through which structure is able to perform well in its lifetime. Other researchers Kong and Frango pol (2003) gave method in which the maintenance of a decline structures and the cost of maintenance of life cycle were presented. This study also analyzed an existing reinforced concrete bridge for illustrating this proposed methodology.

Li and Guo (2017) have done research on four buildings of Taiwan University for finding life cycle cost analysis. They used data of past 42 years, to develop prediction model of life cycle cost.

Kim and Frangopol (2016) gave a path to forecast the perfornance of structures with the help of structural health monitoring (SHM). The aim of SHM is to recognise as evaluate structural performance, forecast remaining service life and offering a decision tool for optimum planning of maintenance.

Passer et al. (2014) showed the results of a pre-feasibility study to recognize future indications for the construction industry in favour of sustainability: Three buildings of office with load bearings systems made of reinforced concrete, steel and timber were collate. A life cycle (LCA) was undertaken. It is judged about the assets of sustainable construction related with different construction techniques can already be assessed. The result is that the three construction techniques are very similar with each other and other construction technique is not preferred only on the assessment of It is required to life cycle. Widened the one-dimensional environmental assessment by joining the two other pillars of sustainability with holistic deliberations fulfill three dimensions of sustainability. Regarding the buildings requirements such as safety and durability for use must also be taken into account in a new dimension called sustainability of structures.

Bowyer (2013) showed a report to make clear the differences between Life Cycle Cost Analysis (LCCA) and Life Cycle Assessment (LCA), shortly highlight about the life cycle costs of non-residential wood construction, comparing the life cycle costs of wood structures to other materials, and review are taken for conducting analysis life cycle cost on structural systems or whole buildings. Short and clear descriptions of LCCA resources are also provided.

## 3. Degradation of Concrete Structures

Service life is the time period after construction during which the desired performance necessity are satisfied. It may also be defined as “Period of time after manufacturing or installation during which all essential properties meet or exceed minimum acceptable values, when routinely maintained” (Masters and Brandt, 1987).

### Deterioration of concrete structures

Deterioration of concrete structures before it have served its expected life is a global phenomenon and the situation is particularly severe in hot and arid regions of the world where high temperature, humidity and salinity exist.

The useful service life of a concrete structure is typically a function of corrosion rate of the reinforcement. Before the corrosion to start, aggressive elements such as chlorides or carbon dioxide must penetrate the concrete in sufficiently high concentrations, to the depth of the embedded reinforcing steel. Corrosion of steel is an expansive process. The process fractures the surrounding concrete and weakens the steel as it rusts. Concrete can also deteriorate because of chemical reactions between and within the cement matrix, aggregate and moisture. Various deterioration mechanisms of concrete structures are shown in figure 3.1 and various factors affecting the condition of concrete structures are shown in figure 3.2. Once damages and initial defects are found, appropriate remedial measures should be taken corresponding to the degree of its effect on the functions of the structure. In cases when any defect has been confirmed, whether the deformation is deterioration, damage or initial defect should first be identified. Deterioration mechanism should be identified in case of deterioration. Cracks or deformations that have been predicted in design are not included in defects. Deterioration factors and phenomenon of various deterioration mechanisms are listed in Table3.1.

**Table 3.1:** Mechanism and causes of concrete deterioration

| | Phenomena |
|---|---|
| Freeze-thaw action | Frozen and defrosting of water in concrete create declination of concrete surface e.g., micro cracking and pop-outs. |
| Chemical attack | Concrete which is hardened in contact with acidic substances is dissolved, or concrete decline due to the pressure due to the creation of chemical substances |
| Alkali-silica reaction | Silicate minerals which are reactive contained in or carbonate rocks combines with solution whose pH is high and it makes irregular expansion or concrete cracking. |
| Chloride induced deterioration | Rusting of steel in concrete is created by chloride ions and it creates the cracking or peeling of concrete or minimizing the cross section of steel. |
| Carbonation | Lowering of pH in pore solution due to the reaction between carbon dioxide and cement hydrate makes the rusting of steel and it causes the cracking of concrete or reducing the steel cross section. |
| Abrasion | Wearing by running water or wheel cause |

Most of these processes are directly responsible for deterioration of the concrete, the discussion of which is outside the scope of this dissertation. However, carbonation of concrete leading to corrosion of reinforcement is the major issue to be addressed in this dissertation.

## 4. Life Cost Analysis

### 4.1 Background

Life cycle cost (LCC) can be defined as the total cost for a customer of a machine or apparatus, including procuring costs and operating costs (which includes preservation, repair, and energy costs). Future operating costs are discounted to the time of purchase and summed over the lifetime of the appliance or equipment.

Life cycle cost analysis as applied to buildings, sometimes also referred to as value engineering or life cycle costing, involves accounting for all costs related to construction, operation, maintenance, and disposal at the end of the useful life of a structure. The purpose is to provide a basis for selection of the most cost-effective design alternative over a particular time frame, taking into account anticipated future costs as well as initial costs of construction. LCCA is especially when investment, operating, maintenance, and repair costs differ, and/or when alternative designs may have different expected service lives.

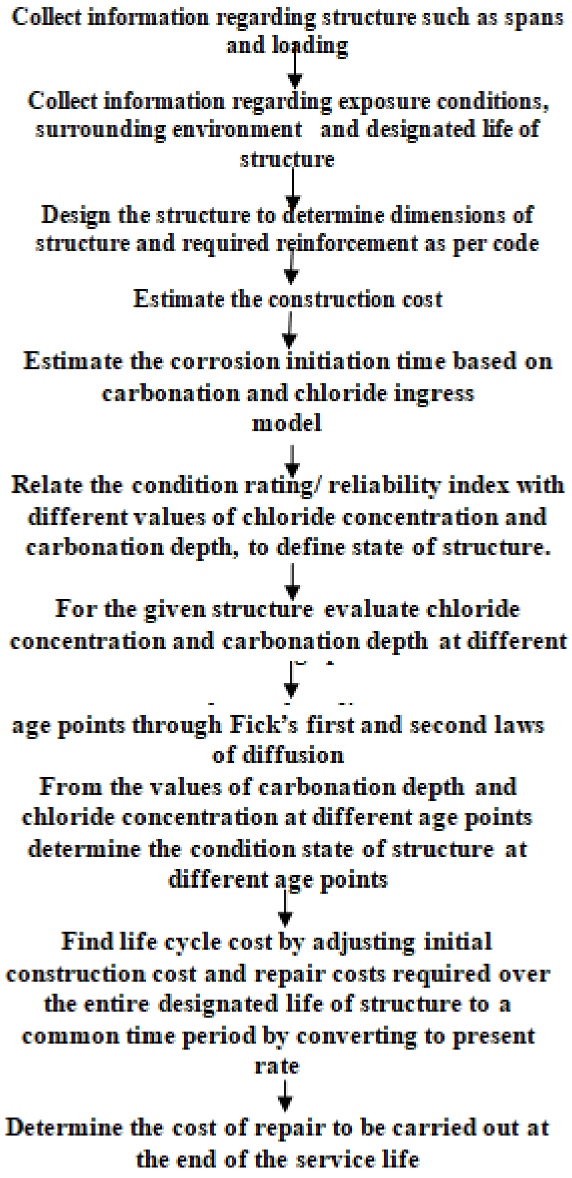
Whole life cycle costing (WLCC) has been becoming a standard method for the long-term cost evaluation of building and civil infrastructure projects. In the context of civil engineering structures rehabilitation, the purpose of a Life Cycle Cost Analysis (LCCA) is to investigate the overall costs of curing methods and select the best one which confirms that constructed facility will provide the lowest overall cost with its quality and function. Nowadays owners are demanding a project that ensures value for money over the life of structures. WLCC has become a crucial device for those concerned in the design, construction, operation and risk investigation of construction projects.

Life-cycle cost is the total customer cost over the life of a piece of equipment, including purchase cost and operating costs (which are comprised of energy costs, maintenance costs, and repair costs). Future operating costs are discounted to the time of purchase and summed over the lifetime of the equipment.

The discount rate (r) is the rate at which future expenditures are discounted to establish their present value. The cost of capital is commonly used to estimate the present value of cash flows to be derived from a typical company project or investment. Most companies use both debt and equity capital to fund investments, so their cost of capital is the weighted average of the cost to the company of equity and debt financing.

### 4.2 Development of LCC Design Model Procedure for life cycle cost modeling

The life cycle cost (LCC) based design procedure is developed for limit state related to the corrosion in reinforcement of RC concrete. This limit state corresponds to initiation of corrosion. Figures 4.2 is a flow chart listing the stepwise design procedure for the above limit state. Hence, the probability of failure of the structure based on above defined limit state increases and the reliability index corresponding to this probability of failure decreases.



Collect information regarding structure such as spans and loading

Collect information regarding exposure conditions, surrounding environment and designated life of structure

Design the structure to determine dimensions of structure and required reinforcement as per code

Estimate the construction cost

Estimate the corrosion initiation time based on carbonation and chloride ingress model

Relate the condition rating/ reliability index with different values of chloride concentration and carbonation depth, to define state of structure.

For the given structure evaluate chloride concentration and carbonation depth at different

age points through Fick's first and second laws of diffusion

From the values of carbonation depth and chloride concentration at different age points determine the condition state of structure at different age points

Find life cycle cost by adjusting initial construction cost and repair costs required over the entire designated life of structure to a common time period by converting to present rate

Determine the cost of repair to be carried out at the end of the service life

**Fig. 4.1:** Flow chart describing steps of design

In the framework of durability based design, the service life of a structure is defined as the time at the end of which maintenance or repair is required to bring the structure to a suitable level of condition/reliability

### 4.3 Case Study

For the illustration of steps in above flow chart, a RC building is considered with the following details.

Time period or age of the structure at which corrosion of rebars will initiate is required to be estimated using Fick's laws of diffusion. Corrosion initiation time can be evaluated through carbonation and chloride ingress models presented in eqn. 4.1 and 4.2. Lowest value among the values obtained from these two models is considered as a corrosion initiation period.

**Corrosion initiation period using Carbonation model**

Carbonation models are based on Fick's first law of diffusion is

$$d = K.\ t^{1/2} \qquad (4.1)$$

Where d is carbonation depth, t is age of the structure and K is the coefficient of carbonation.

**Corrosion initiation period using Chloride ingress model**

### 4.4 Repair techniques

Corrosion leads to the destruction of the protective oxide film developed in alkaline environment. If the chloride could be removed and PH is again reestablished to provide protective film problem can be resolved.

**Example 1**

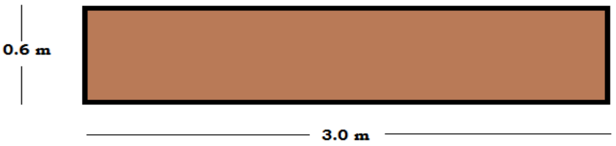


**Figure –** Rectangular Beam

Pr = replacement cost;

m = percentage of component required to be replaced = 50%= 0.5, as only concrete surrounding rebars is required to be replaced;

i = annual inflation rate i.e. 4% = 0.04;
N = estimated service life = 27 years;
Pc = construction cost = 10049.72/-

**Renewing or replacement cost** can be calculated by the relation proposed by Heidler (1994) as shown below –

So, Pr = 10049.72 x 0.5$(1.04)^{27}$ = 14488.52/-.

If replacement of 50% of concrete is provided then replacement cost after 27 years is 14488.52/-. This cost can be converted to its present value using eqn. 5.4.

So present value of Pr = 3880.72/-

However, if no repair is provided at the time of corrosion initiation, and repair or replacement of beam is performed at the 40 years of age, time of failure then it costs –

Pr = 14488.52 x1.00 $(1.04)^{40}$ = 69559.68/-

So, it has been concluded that replacement cost after the failure, if no repair is provided, is almost 15-20 times the repair cost, if provided, at the time of corrosion initiation.

Hence, it is better to replace damaged concrete at regular interval of time to avoid early failure of structure. Here, in the present study for designated life of 50 years if repair or replacement of corrosion affected concrete is performed after interval of 10 years i.e. at age of 27, 37 and 47 years by replacing 50%, 60% and & 75% of concrete then total replacement cost is

Pr = Pr (27) + Pr (37) + Pr (47);

Pr (27) is already estimated as 3880.27/-.

For estimating Pr (37) initial construction cost is obtained by adding Pr (27) and value of 10049.72 at the age of 27 years
Pr (37) = (10049.72*$(\mathbf{1.05})^{27}$ +14888.52) * 0.6 $(1+0.04)^{10}$= 46546.62/-.

So, present value of Pr (37)= 7653.92/-
Pr (47) = (10049.72*$(\mathbf{1.05})^{37}$+3880.27*$(\mathbf{1.05})^{10}$+36821) * 0.75 $(1+0.04)^{10}$ = 115745.47/-
So, present value of Pr (47)= 16651/-

Therefore, **Pr** = 4404+ 8621+ 16651 = **29676/-.**

In general, inspection is performed for detecting corrosion of rebars and formation of cracks, and thus requires modern non- destructive techniques (NDT), Inspection cost for first year can be considered as a fraction of initial construction cost i.e. 0.07 of construction cost (Frangopol et al.), when no damage is detected.

Therefore, inspection cost for first year is

0.07 * 11406=799/-.
Further inspection costs for future years can be calculated using.

Pi = inspection cost for whole life of the structure i.e. designated life of structure.
Pin = inspection cost for first year of the life of structure = 799
D = designated life of structure = 50 years
S0, Pi = **9156**/-

Preventive maintenance and repair cost **Pm** can be evaluated according to the frequency of inspection. According to Frangopol et al. (2000)

Where Cmain = cost of preventive maintenance at year one; and t= age of concrete in years. For the present study if preventive maintenance is scheduled at the age of 10, 20, 30 and 40 years so total cost for maintenance is

$$Pm = Cmain,10/\ \mathbf{(1+r)}^{10} + Cmain,20/\ \mathbf{(1+r)}^{20} + Cmain,30/\ \mathbf{(1+r)}^{30} + Cmain,40/\ \mathbf{(1+r)}^{40}\ ;$$

Considering Cmain as 0.05 fraction of initial construction cost = 570

**Pm** = 3500 + 4300 + 3957+ 3239 = **14999/-**

Hence total life cycle cost for the beam is estimated as

**Total cost** = 11406 + 29676+ 9156+ 14999 = 65237/-

## 5. Figures and Tables

**Figures-**

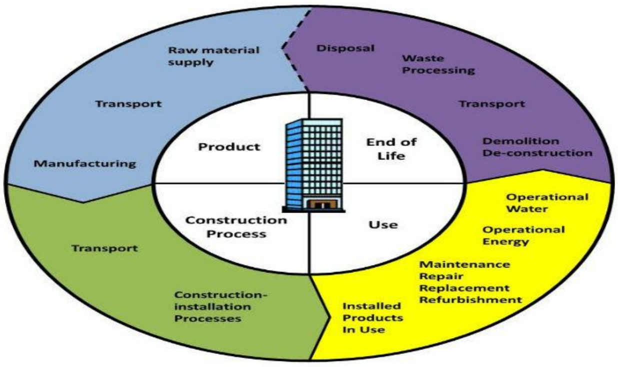


**Figure 1.1** – Costs involved in life of a structure

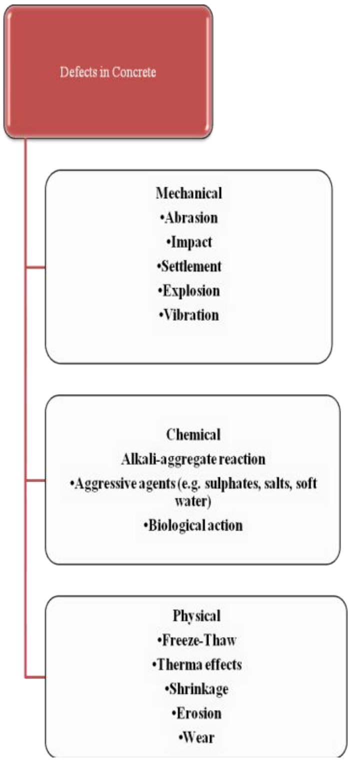


**Figure 3.1** – Various deterioration mechanisms

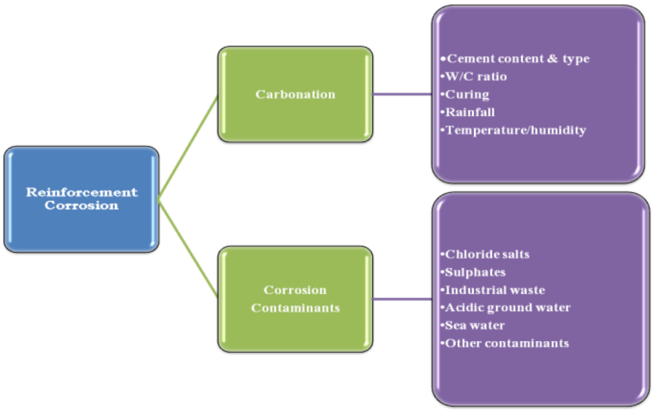


**Figure 3.**2–Factors affecting condition of concrete structures

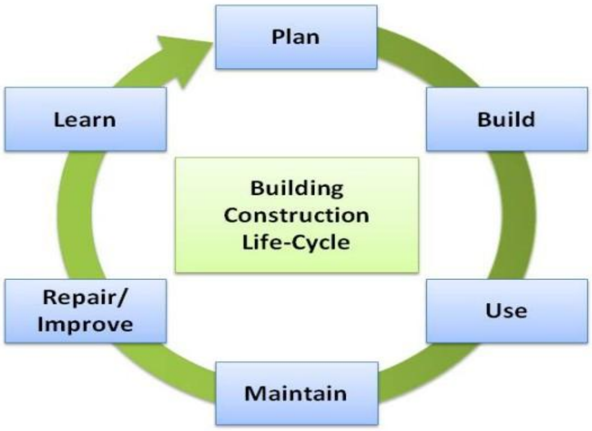


**Fig 4.1** Life cycle of a concrete structure

## Tables

**Table 3.1** – Mechanism and causes of concrete deterioration

| S. No. | Parameter | Value |
|---|---|---|
| 1 | Designated life of structure | 100 years |
| 2 | Present age of structure | 20 years |
| 3 | Compressive strength | 25 MPa |
| 4 | Concrete cover | 40mm |

**Table 4.2 –** Details of structure considered

| Reliability index | Condition | Repair Priority |
|---|---|---|
| 100 | Ratio of Carbonation to Cover depth<1 and Chloride concentration by weight of concrete < 0.2 | No repair |
| 80 | Ratio of Carbonation to Cover depth>1 and Chloride concentration by weight of concrete < 0.2 | Very low priority repair, Repair can be delayed for longer time |
| 60 | Ratio of Carbonation to Cover depth<1 and Chloride concentration by weight of concrete between 0.2 and 0.3 | Corrosion initiates and Immediate repair action should be taken |
| 40 | Ratio of Carbonation to Cover depth>1 and Chloride concentration by weight of concrete between 0.2 and 0.3 | High priority repair, Repair should be undertaken as early as possible |
| 20 | Ratio of Carbonation to Cover depth<1 and Chloride concentration by weight of concrete >= 0.3 | Condition is critical, Repair is of extremely high priority |
| 0 | Ratio of Carbonation to Cover depth>1 and Chloride concentration by weight of concrete >= 0.3 | Failure |

**Table 4.3 –** Estimation of construction cost

| | | | | | | |
|---|---|---|---|---|---|---|
| DATA GIVEN | IN METRE | FOR CONCRETE | | | | |
| WIDTH | DEPTH | LENGTH | VOLUME | CONCRETE S.O.R FOR CU.M. | RATE IN RUPEES | |
| 0.6 | 0.5 | 3 | 0.9 | 7000 | 6300 | |
| | | | | | | |
| DATA GIVEN | IN METRE | FOR CENTRING | | | | |
| WIDTH | DEPTH | LENGTH | AREA | CENTERING S.O.R FOR SQ.M. | RATE IN RUPEES | |
| 0.6 | 0.5 | 3 | 6 | 80 | 480 | |
| | | | | | | |
| DATA GIVEN | IN METRE | FOR STEEL | | | | |
| DIA OF BAR | CUTING LENGTH | UNIT WEIGHT | NO.OF BARS | WEIGHT | RATE | RATE OF STEEL |
| 20 | 3.4 | 2.47 | 4 | 29.64 | 90 | 2667.6 |
| Stirrups-8mm@200 mmc/c | 38.4 | 0.39 | 1 | 14.98 | 32 | 479.36 |
| | | | | 44.62 | | |
| BINDING WIRE | S.O.R. RATE RS.3 PER KG | | | 123.2647 | | |
| | | | | | | |
| | TOTAL COST | | 10049.72 | | | |

## 6. Equations

Life-cycle cost is defined by the following equation:

$$\textbf{LCC = IC + } \sum \textbf{OC}_t \textbf{ / (1+ r)} \qquad \textbf{(4.1)}$$

t =1

where

LCC = life-cycle cost,
IC = total installed cost,
Σ = sum over the lifetime, from year 1 to year N, where N = lifetime of equipment (years),
OC = operating cost,
r = discount rate,
t = year for which operating cost is being determined.

Corrosion initiation time using chloride ingress model has been evaluated through eq. 5.2

$$\mathbf{tinit} = \frac{c^2}{4D}\left[\mathrm{erf}^{-1}\left(1-\frac{Cth}{Cs}\right)\right]^{-2} \qquad \textbf{(4.2)}$$

Considering c=40mm, cth= 0.2 (% wt. of concrete), cs = 0.6 (% wt. of concrete), and D= 1 x $10^{-12}$ $m^2$/ sec, value of corrosion initiation time obtained is **27.14 years.**

Total life cycle cost can be estimated by considering construction cost (Pc), inspection cost (Pi), maintenance or repair cost (Pm), and renewing/ replacing cost (Pr), so the formula is

**Total cost = Pc + Pi + Pm + Pr + miscellaneous costs (4.3)**

All the above costs should be should be adjusted to the study time though discount rate ‘r’.

$$\textbf{Present cost = cost to be adjusted/ } \mathbf{(1+r)^{t}} \qquad \textbf{(4.4)}$$

Where, t is number of years between the date of investment and present time and r is the net discount rate of money. Considering r = 0.05.

$$\textbf{Pr = Pc x m } \mathbf{(1+i)^{N}} \qquad \textbf{(4.5)}$$

$$\textbf{Pi = Pin } \mathbf{(1+r)^{D}} \qquad \textbf{(4.6)}$$

$$\textbf{Cmain, t = Cmain x t;} \qquad \textbf{4.7)}$$

## 7. Discussion and Conclusions

1. A life cycle cost estimation process for reinforced concrete structures has been presented in this research. The method attempts to incorporate issues of structural service life and durability together with financial cost optimization into the structural design process.
2. The estimation of structural performance and durability is made on the basis of determination of the service life of reinforced concrete structures. The service life is determined based on the concept of exceeding limit states that is commonly used in structural design.
3. Limit state is based on the initiation of corrosion. The service life hence determined decides the amount and timing of the future costs to be incurred during the design life of the structure. The life cycle cost is then determined based on discounting of the initial construction cost and the future repair costs to present values to ensure a time-consistent comparison of costs.
4. Replacement cost after the failure for concrete structures, if no repair is provided, is almost 8-10 times the repair cost, if provided, at the time of corrosion initiation.

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